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IDA MEMORANDUM REPORT M-199

GLOBAL EFFECTS SIMULATION STUDIES

Ernest Bauer
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November 1986

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Defense Nuclear Agency

INSTITUTE FOR DEFENSE ANALYSES
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This document reviews the initial rise of a fire plume in the atmosphere, including effects of the condensation of entrained atmospheric moisture. The condensation, expansion, and evaporation of the water cloud are examined, as are the relative effects of scattering and absorption in radiation transport through the gray-white smoke plume and a wood fire. For applications to the Nuclear Winter problem, the following points are made as recommendations for further work in critical areas:

1. The climatic impact of a smoke plume depends significantly on its height in the atmosphere, which is affected by long-term atmospheric motions and in particular by solar-induced buoyancy as well as by the initial plume rise. This long-term behavior can be studied by using Arctic Haze data.
2. For a given optical thickness, the absorptive (black, sooty) component of smoke (due largely to oil and oil-related fuels) is much more effective in reducing the transmission of sunlight and thus in producing climatic cooling than is the largely scattering (white/gray) component which predominates in most wood fires. The smoke characteristics tend to change with time, and thus for climatic application should be investigated as late as possible after injection into the atmosphere. This, in turn, requires using smoke from the largest possible sources which can be studied for the longest times. Explicitly,
   a. For forest fires, the satellite analysis of Fraser et al. (1986) has been used for 1- to 3-day old smoke following the very large 1982 Yukon fires; the results need to be validated.
   b. For oil fires, even the largest sources are much smaller than for wood (forest/agricultural) fires; perhaps the best approach here is to follow the plume of an oil pool fire, e.g., at Sandia National Laboratory, for several hours by using a sampling aircraft.
3. Actual smoke plumes are always nonuniform, even at late times. This reduces the effective extinction and cooling due to a given amount of smoke over the case of a uniform distribution. Experimental study of large fire plumes to late times will provide a measure of the reduction in cooling over a uniform distribution that is to be expected.

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PREFACE

This is the final part of work performed by IDA for DNA under Amendment 1 to Task Order T-4-237 (see Appendix A). The effort applies to the "Nuclear Winter" hypothesis, and addresses the partial simulation of this scenario by very large forest and industrial fires, and in particular, the observation of the smoke plumes by using weather satellite imagery. The first and major part of this effort was reported under M-116 (December 1985). It consists of two items, namely, a panel report on the use of existing data from weather satellites to study large (forest and industrial) fires as experiments of opportunity and, as an example of what can be done, a preliminary report on what one can learn from the December 1982 fire of a large crude oil storage tank at Tacoa, Venezuela. A revised version was presented at the 1986 IRIS Targets, Backgrounds, and Discrimination Meeting, and will appear in the Proceedings. The summary of M-116 is included as Appendix B.

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Useful comments and material have been received from Art Aikin and Bob Fraser (NASA/GSFC), Joe Knox (LLNL), Bob Malone (LANL), Mike Matson (NOAA/NESDIS), Rich Turco (RDA), and Bernie Zak (SNL). In particular, the reviews of Don Alderson (KAMAN-TEMPO), Hal Brode (PSR), and Bob Oliver (IDA) were invaluable in pulling the material together.

ABSTRACT

This document reviews the initial rise of a fire plume in the atmosphere, including effects of the condensation of entrained atmospheric moisture. The condensation, expansion, and evaporation of the water cloud are examined, as are the relative effects of scattering and absorption in radiation transport through the gray/white smoke plume from a wood fire. For application to the Nuclear Winter problem, the following points are made as recommendations for further work in critical areas:

1. The climatic impact of a smoke plume depends significantly on its height in the atmosphere, which is affected by long-term atmospheric motions and in particular by solar-induced buoyancy as well as by the initial plume rise. This long-term behavior can be studied by using Arctic Haze data.
2. For a given optical thickness, the absorptive (black, sooty) component of smoke (due largely to oil and oil-related fuels) is much more effective in reducing the transmission of sunlight and thus in producing climatic cooling than is the largely scattering (white/gray) component which predominates in most wood fires. The smoke characteristics tend to change with time, and thus for climatic application should be investigated as late as possible after injection into the atmosphere. This, in turn, requires using smoke from the largest possible sources which can be studied for the longest times. Explicitly,

a. For forest fires, the satellite analysis of Fraser et al. (1986) has been used for 1- to 3-day-old smoke following the very large 1982 Yukon fires; the results need to be validated.

b. For oil fires, even the largest sources are much smaller than for wood (forest/agricultural) fires; perhaps the best approach here is to follow the plume of an oil pool fire, e.g., at Sandia National Laboratory, for several hours by using a sampling aircraft.

3. Actual smoke plumes are always nonuniform, even at late times. This reduces the effective extinction and cooling due to a given amount of smoke over the case of a uniform distribution. Experimental study of large fire plumes to late times will provide a measure of the reduction in cooling over a uniform distribution that is to be expected.

CONTENTS

SUMMARY

The Tacoa, Venezuela, oil fire discussed earlier in this study (see Part II of M-116) produces a white plume which is shown in Fig. 1 (p. 1-2). This is interpreted as the capping cumulus cloud produced by the condensation of water vapor from fuel combustion and the entrainment of moist near-surface air which is transported up to the plume stabilization height in the relatively cold middle troposphere. Such capping cumulus clouds are formed not infrequently from sufficiently large fires under appropriate meteorological conditions (moist and warm lower atmosphere, dry and cold upper atmosphere). Some examples are provided by large forest fires and by large agricultural burns in the tropics (see Fig. 2, p. 1-5, for example). The direct climatic effect of the capping cloud is not large because it evaporates rapidly--at most within several hours--but because the latent heat of condensation of atmospheric water vapor in the plume is released during the plume rise, it will cause the plume to rise higher than it would rise without this energy input.

The climatic impact of a smoke layer depends on its altitude, with a higher layer producing significantly more cooling than a lower-altitude layer. The altitude distribution of smoke is affected not just by its initial injection but also by the long-term motion in the atmosphere including, in particular, its solar-induced buoyancy; perhaps the best way to study or simulate this is by using Arctic Haze as a model, where on occasion near-surface emissions from a metal smelter at Norilsk, Siberia, have been tracked for approximately ten days as the source of a 3-km-high layer over Alaska (in the AGASP program see Schnell et al., 1984).

Here a preliminary discussion is given of the plume rise for different types of fires, including crude estimates of the lifetime of the water plume, and also of the optical properties of the residual smoke plume. Especially for a wood fire, the (gray/white) smoke plume mainly scatters sunlight rather than absorbing it like an idealized black soot plume. For a given dimensionless optical depth, the transmission of sunlight through a scattering plume is much greater than that through an absorbing plume, and thus the "Nuclear Winter" cooling of an absorbing smoke (e.g., from oil) is much greater than that from a scattering smoke (e.g., from wood).

Estimates of Lawrence Livermore National Laboratory (Knox et al., 1986) indicate that the fuel in a urban/industrial location is typically 20 percent oil and oil-based material (plastic, etc.) as against 80 percent for wood, paper, etc., so that the scattering effects will be important.

Because smoke characteristics change with time, it is important to measure the late-time optical properties of smoke from both wood and oil fires. This requires the largest possible fires whose plumes can be followed for a relatively long time. (Wall effects make long-term laboratory studies of smoke properties infeasible or probably unrepresentative.) Fraser et al. (1986) have studied the smoke plume of a very large series of forest fires (2.5 million acres in Yukon, July 1982) for up to three days, by an as-yet-unvalidated method which uses satellite imagery. This method should be validated and extended. Oil fires are typically much smaller: the very large Tacoa oil fire had a smoke generation rate perhaps 1/30 that of the Yukon fires (see M-116) and cannot be studied in this way. To study late-time smoke from an oil fire, it may be appropriate to use the Sandia National Laboratory's pool fires with a sampling aircraft which can presumably follow the plume for several hours.

By studying a fire plume for an extended time, one can investigate its patchiness under representative conditions. This will be important for computing climatic cooling because an individual smoke plume is never uniform (although the average over many different plumes will be uniform). If a given amount of smoke is distributed uniformly in a horizontal plane, its extinction will be a maximum, so that this nonuniformity will lead to a possibly significant reduction in cooling. A simple model (given in Appendix D here) suggests that for optical thickness 3 a reduction by perhaps a factor of 1.5 to 8 is possible.

From the standpoint of their potential impact on the anticipated climatic ("Nuclear Winter") cooling, the following recommendations for further work are offered:

1. Use Arctic Haze data to study the motion of plumes of pollutants at very late times (up to ten days).
2. Validate the satellite analysis of optical properties of wood smoke plumes at very late times (days).
3. Study the optical properties of smoke from oil fires (sooty) as late as possible (up to several hours)
4. Study nonuniformities of smoke plumes in the atmosphere at late times.

1. INTRODUCTION

In Part II of M-116 (Bauer, 1985; see also Bauer, 1986) the characteristics of the smoke plume of the oil fire of 20 to 22 December 1982 at Tacoa, Venezuela, were analyzed and shown to be largely due to water droplets, evidently from the condensation of moisture generated by combustion and also ambient moisture transported up to the stabilization height of the plume. Figure 1 shows visible satellite imagery from NOAA-6, and one sees that the smoke plume looks white, like a water (or ice) cloud. While the fire was large in terms of oil fires (the largest reported between 1970 and 1984 on a worldwide basis), its plume could not be seen on satellite imagery for more than five hours.[1]

Table 1 reviews the general characteristics of stabilized plumes due to large oil fires. Oil is well known to burn with a smoky flame, but nevertheless the stabilized plume is sometimes black and sometimes (near) white. For comparison, Table 2 gives equivalent information on wood fires. Smoke from intense forest fires is often dense black also (generally when combustion occurs under fuel-rich conditions), but usually the plume turns white at some altitude, due to the condensation of atmospheric moisture. A capping cumulus cloud is sometimes produced, and it may survive for some hours.

For the Global Effects/Nuclear Winter application, the main contribution comes from urban rather than forest fires.

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[1]Figure 1 shows the plume at 7:00 a.m. LT. GOES imagery at 12:00 LT displays a number of smaller plumes, while the NOAA polar orbiter overflight at 2:42 p.m. shows so much cumulus that the fire plume can no longer be detected.

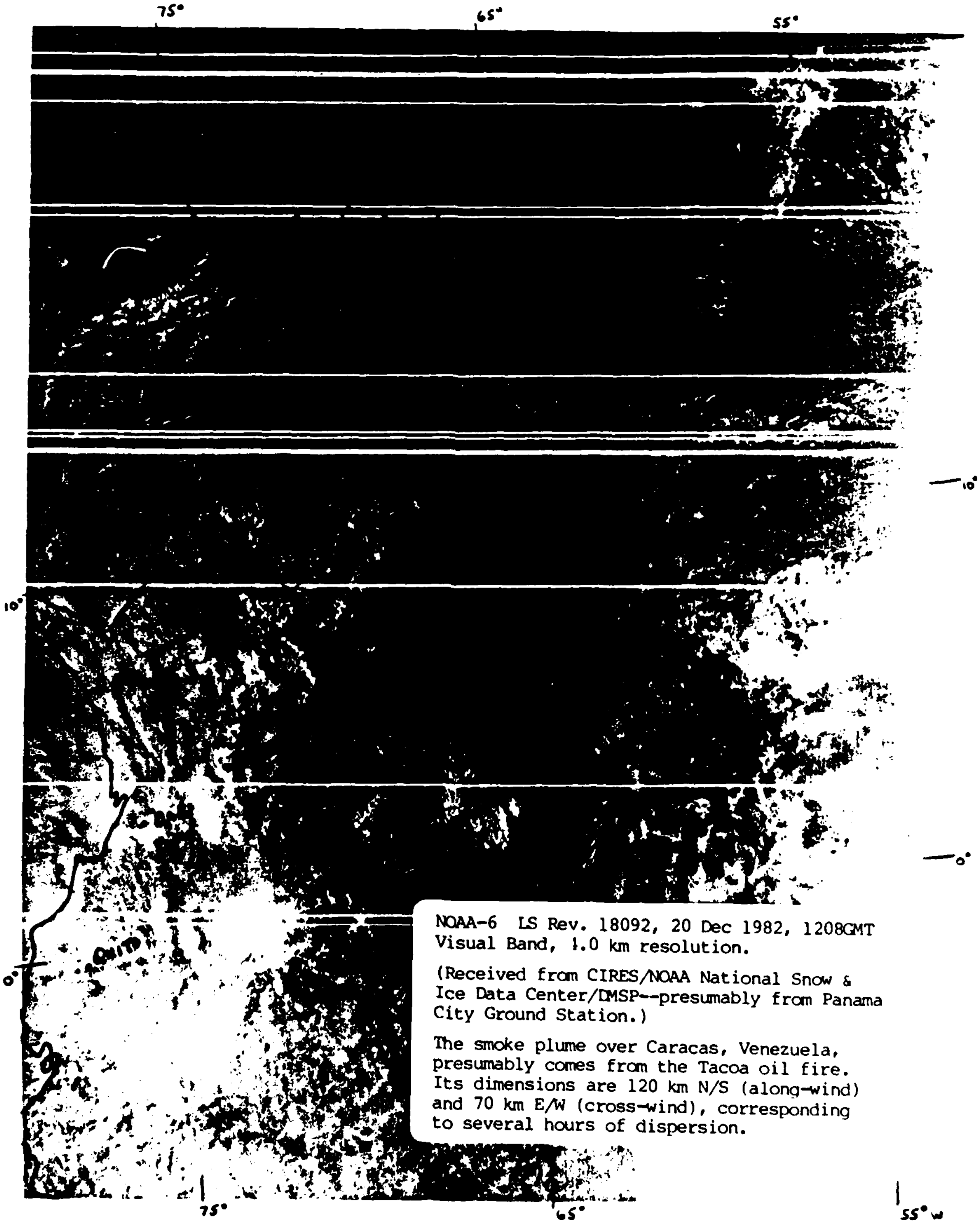

FIGURE 1. Visible Satellite Imagery from NOAA-6, 7:08 a.m. LT on 20 December 1982 (1 km resolution) showing the smoke plume from the Tacoa, Venezuela oil fire over Caracas.

TABLE 1. CHARACTERISTICS OF STABILIZED PLUMES FROM OIL FIRES

- Oil burns with a sooty flame, but the stabilized plume is sometimes black, sometimes white.

- Oil storage tanks at Tacoa, Venezuela burned on 20 December 1982; the plume was white.[1]

- Fire at an oil refinery in Long Beach, California on 22 May 1958 produced a black plume.[2]

- Meteotron, S. France (large array of oil burners) produced a stabilized plume that was sometimes black, sometimes white.[3]

- 1 kg oil requires 15 kg air for combustion and produces a "relatively large" quantity of black, sooty smoke, also ~ 1.3 kg water of combustion.

- During its rise to stabilization, the plume from a high-energy fire entrains a large quantity of near-surface, i.e., relatively moist, air which it takes to its stabilization altitude. As a crude estimate, we shall assume a 100:1 dilution of the plume by entrainment of air.

- The atmosphere at Tacoa, Venezuela would be very moist (~ 4.5 g/cm^2 precipitable water) while that at Long Beach in May would be fairly dry (~ 1.5 g/cm^2) (see Appendix C).

- Thus, 1 kg fuel produces perhaps 100 to 200 g smoke, including perhaps 10 to 50 g soot, and also brings $\gtrsim$ 2000 g water (from combustion and entrainment) to stabilization in the atmosphere.

---

[1]NOAA-6 satellite imagery (see Bauer, 1985) who points out that for mean particle size $\gtrsim$ 0.1 μm, the mass of the plume is significantly greater than a plausible mass of soot, i.e., can only be condensed water.

[2]Davies (1959).

[3]L. Radke (University of Washington), private communication.

[4]Fresh soot consists of very small (~ 0.01 μm) hydrophobic particles with a C/H ratio of about 12/1 by mass. The particles tend to agglomerate as they age.

TABLE 2. SOME CHARACTERISTICS OF WOOD SMOKE

- Wood fires (forest or agriculture) generally produce a white or gray smoke plume.

- When a wood fire burns fuel-rich, e.g, as it reaches a large supply of fuel, the smoke may turn black momentarily, but generally it soon turns white again.

- Flaming combustion gives a relatively small quantity of sooty smoke while smoldering combustion produces a relatively large quantity of white or gray smoke.

- 1 kg wood requires approximately 5 kg air for combustion, producing approximately 0.6 kg water of combustion, 1.5 kg CO_2, significant quantities of CO and other gaseous molecules including hydrocarbons, plus 100 to 200 g gray/white smoke (made up of complex organic molecules, mainly liquid droplets, but including perhaps 10 to 50 g soot.

An analysis by Lawrence Livermore National Laboratory (LLNL), Knox et al. (1986), p. 19, finds that available urban fuel is typically 15 to 20 percent oil or oil-based (plastic, etc.) which would be expected to produce black, sooty smoke, while the remaining 80 to 85 percent is wood or wood-based (paper, etc.) which tends to produce white/gray smoke that scatters sunlight rather than absorbing it. Even if the smoke generation rate and particle size distribution are the same, the quantitative cooling effectiveness of white and black smoke will be quite different.

Here the problem of plume rise and the condensation and evaporation of moisture in a fire plume is reviewed briefly, largely for the case of wood fires. Figure 2 shows agricultural burning in Brazil, where the large fire (A) appears to produce a capping cloud, while smaller fires such as (B) do not. (The capping cloud of fire (A) has horizontal dimensions of 20 to 30 km.)

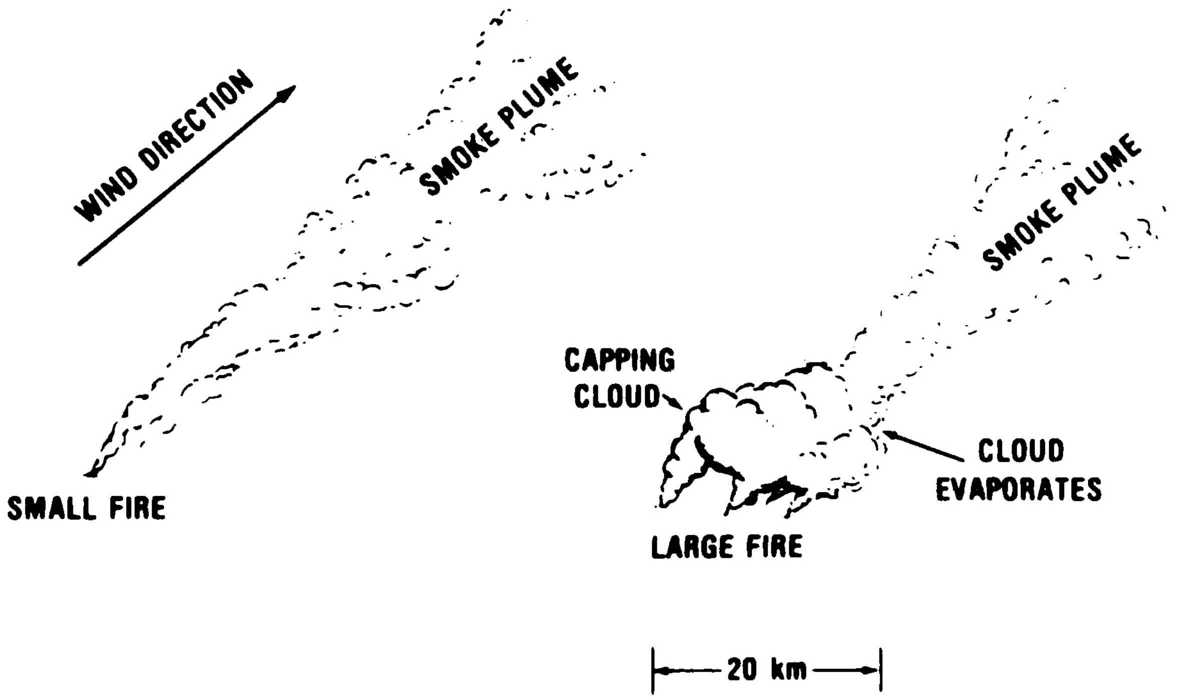

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FIGURE 2. Development of smoke plume from small and large fires. (Sketched from space shuttle photograph #41-D-31-108 of land clearing in Brazil in August 1984.)

2. PHENOMENOLOGY

2.1 GENERAL COMMENTS

Reference to Tables 1 and 2 shows that the combustion of 1 kg fuel yields 0.1 to 0.2 kg smoke in addition to ~ 1 kg of water of combustion. In addition, some 1 to 10 kg atmospheric water vapor is entrained with the relatively moist near-surface air and is taken to stabilization in the plume. Thus, the smoke plume always contains much more water vapor than "smoke". During the plume rise to stabilization into a colder atmosphere, the excess water vapor may condense to form a capping cumulus cloud, provided the fire is sufficiently energetic and the atmosphere is sufficiently moist (see Appendix C for a discussion of atmospheric moisture).

The details of plume rise, entrainment, condensation, and stabilization are complex and are reviewed in Section 2.2 below. The physical details of how the condensation occurs are not well understood; it probably will not occur on soot particles nor on large organic molecules, all of which tend to be hydrophobic. Rather, it probably occurs on inorganic ash particles or on sulfuric acid droplets (which result from the oxidation of sulfur present to a few percent in oil or coal, but not in wood). In any case, there are usually more than sufficient condensation nuclei for aerosols to form.

The formation, spreading, and (relatively rapid) disappearance of a water cloud is discussed briefly in Section 2.3, and the late-time behavior of smoke is treated in Section 2.4. Section 2.5 reviews the optical properties of smoke from both wood and oil fires, raising some major unresolved questions on the composition of smoke and thus on the relative contribution of scattering and absorption to extinction in the visible. Finally, the climatic effects of smoke are briefly summarized in Section 2.6.

2.2 PLUME RISE

A large fire provides a substantial source of energy with mass injection (including water and smoke) on an appropriately large geometrical scale, which gives rise to a (turbulent) buoyant plume that entrains ambient air as it rises to its stabilization height in the atmosphere. These qualitative characteristics of the overall plume behavior are understood, but as yet no simple, general, and quantitative description of the motion has been given. Thus Briggs (1969), in an evaluation of the rise and stabilization of chimney plumes, reviews some thirty different formulas that predict how effluents from nuclear power plants are dispersed into the atmosphere. He finds no single simple but generally useful model for the process.

The flow field induced by a source of buoyancy, with or without mass injection, has been modeled by many investigators. Morton, Taylor, and Turner (1956) treated steady point sources and instantaneous releases (thermals) in uniform and uniformly stratified atmospheres. Their result for the maximum height of the plume, h_{max}, from a steady source of heat, Q, in a uniformly stratified, quiescent atmosphere is a simple power law. For the case of a surface temperature of 288 K and a lapse rate (rate of decrease of temperature with height) 6.5 C/km, they obtain the result

$$h_{max} = 46 \ Q^{1/4} , \qquad (1)$$

where h_{max} is measured in meters and Q in kilowatts.

Morton (1957) extended this formulation to include the effect of moisture from the heat source and also entrained from the ambient environment. In this case, the power law similarity solution leading to Eq. (1) breaks down at the height at which moisture condensation occurs. As Morton (1957) points out, the fate of the plume above the condensation height may be quite independent of the source, while below it, the solution for a dry atmosphere is an excellent approximation. Thus, if the plume reaches the condensation altitude before it comes to rest, it may rise very little further or, on the other hand, it may rise substantially higher. In many cases, its fate above the condensation height is determined more by the structure of the atmosphere than by the source of buoyancy.

Near the surface of the earth, air contains between a few grams and several tens of grams of water per kilogram of air, depending on location, season, and weather (see, e.g., Appendix C, Fig. C.1). As the plume rises, it entrains and mixes ambient air into the flow, slowing its rise and cooling. If the source of buoyancy is dry (e.g., a source of heat only) then the moisture content of the plume flow at each altitude is due solely to moisture entrained at lower altitudes. However, the combustion of oil or wood produces water approximately equal in mass to the mass of fuel burned, while if live vegetation is included, the water due to its combustion is about twice that for dry wood. Thus, a fire plume will have an initial moisture content substantially higher than does surface air; it is only because it is also hotter that this moisture does not condense immediately.

As the plume rises into the atmosphere, the plume gases expand and cool. Under the assumption of adiabatic condensation, the Clapeyron equation gives a relationship between temperature and saturation vapor pressure of water. This relationship allows one to close the set of equations describing the plume flow, which now contains a variable that describes what fraction of water is in the liquid phase. The difference in density between the plume flow and the atmosphere depends on this apportioning. The density defect vanishes when enough water condenses and the temperature in the plume is low enough--often several degrees below the local ambient. The gases in the plume follow a "wet adiabat" on the temperature-vs-pressure plane, while the moisture fraction evolves according to the water entrainment rate and plume size. While the density defect may be very small (often in parts per thousand) the plume may be very large, so that the forcing term in the equation of vertical motion can still be quite large, as it is proportional to the horizontal section area of the plume multiplied by the density defect. Thus, the plume may rise very slowly, but continue upward for a great distance under the influence of these small forces.

However, this is not the way the process proceeds in nature, since the atmosphere is seldom quiescent. There is a wind, which generally increases in magnitude and changes direction with increasing height. The change in direction is usually due to a balance between shear stress and Coriolis acceleration, resulting in a clockwise rotation with decreasing altitude in the northern hemisphere. At midlatitudes this deviation is about 45 degrees. The wind field in the near-surface atmosphere is quite variable, and local meteorological soundings are necessary for accurate predictions of plume behavior.

In fact, wind is usually the dominant factor in the behavior of a fire plume. Indeed, several investigators have treated the wind-blown plume as embedded in the wind field and evolving under the perturbing influence of buoyancy. A large body of literature exists (see, e.g., Turner, 1960, or Briggs, 1969 for surveys) but the problem is too complex to admit even a crude closed form approximation. Briggs (1969) discusses and compares tens of empirical formulas, finding none of them convincingly robust.

An empirical method used to estimate the height of plumes from wildland fires is not discussed in either of the sources mentioned above. This formula, given in Chandler et al. (1983) defines a quantity ΔT_p in terms of a mean power density q (kW/m^2), the radius of a circle that would enclose the burned area, r_o (m), and the radius r_1 (m) that a plume would have at altitude h if it grew linearly with height at an angle α estimated by the user, where for small, low-intensity fires α = 12 to 18° while for large, high-intensity fires α = 6 to 10°. Here,

$$\Delta T_p = 10.75\, q^{2/3}\, (r_o/r_1)^2 \tag{2}$$

and

$$r_1 = r_o + h \tan\alpha \; . \tag{3}$$

The procedure of Chandler et al. is the following:

1. plot the dry adiabat from the surface to altitude
2. subtract the dry adiabat from the sounding temperature at altitude to obtain ΔT(K)
3. add the ambient wind speed u (m/s) to ΔT to obtain $(u + \Delta T)$ (K).
4. the plume tops out where

$$\Delta T_p = \Delta T + u \; . \tag{4}$$

Table 3 lists some representative input quantities for wildland fires, and also for comparison numbers for the Tacoa, Venezuela oil fire and for the "Meteotron" controlled oil fire, (Church, Snow, and Dessens, 1980). Figure 3 shows some typical profiles for ΔT and $\Delta T + u$ gives the predicted height of plume rise. In Figure 3 we show T_p for the fire C (intense brush or crown fire) from Table 3. For this fire the Morton-Taylor-Turner formula (1) gives a plume rise height of 5.1 km, while the Chandler et al. procedure of Eq. (4) gives a plume

TABLE 3. SOME REPRESENTATIVE FIRES

Code	Type of Fire	Area Enclosed by Fire Perimeter (ha)	Flame Height (m)	Intensity of Area Burning q (kW/m^2)	Radius r_o (m)	Angle of Spread α (degrees)
A.	Small Savanna	10	0.5	50	178	18
B.	Small Forest Fire	10	3	100	178	14
C.	Intense Brush or Crown Fire	100	10	150	564	10
D.	Slash Fire or Land Clearing	500	30	100	1260	10
E.	Tillamook	4500	30+	100	3/85	10
F.	Tacoa Oil Fire	1	?	750	56	10?
G.	Meteotron	2	?	50	80	10?

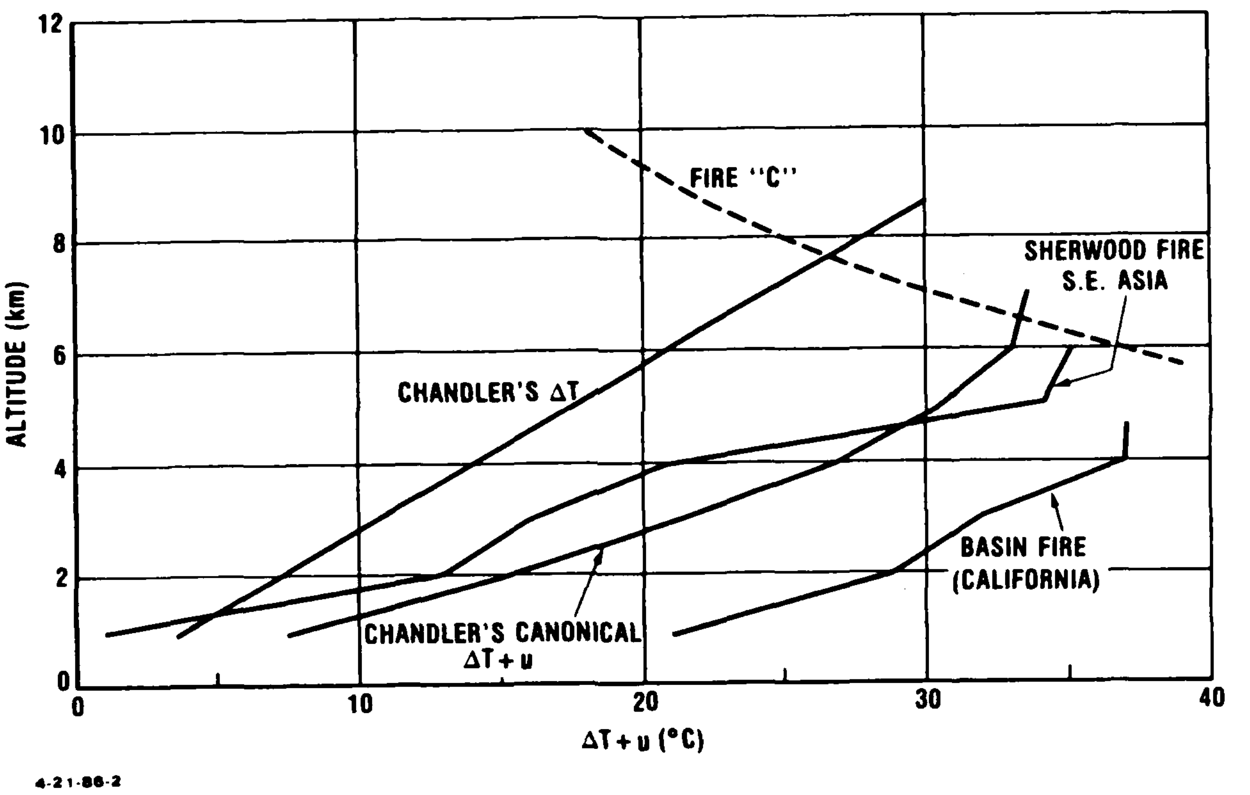

FIGURE 3. Plume rise estimates: $\Delta T + u$ as function of height, and the example of fire "C" of Table 3 [see Eq. (2) of Section 2.2].

height of 6.5 km for Chandler's canonical profile or 7.7 km with no wind; for the California basin fire profile, the plume rise would be 5.5 km, or for the South-East Asian Sherwood fire it is 6.3 km.

These numbers for Fire C are in general agreement with one another, and with the predictions for the Morton-Taylor-Turner formula (1) if one assumes that the entire burned area is alight and burning with the power density used for the empirical calculations. Comparable agreement is obtained for the other wildland fires A-E. The fact that these results agree might give a misleading impression of the physics. Recall that the Morton-Taylor-Turner formula applies to a point source; to apply this to the 4500 ha Tillamook burn is unreasonable.*

To emphasize this point, the fires listed in Table 3 were represented by the parameters listed in Table 4 which estimate the actual area burning at one time and the power generated, and computations were performed by a numerical integration of equations equivalent to those given by Morton (1957).

Above the condensation height h_c, these equations were augmented by one for a wet adiabat and an explicit calculation of the density defect. The numerical model was exercised using the fire parameters in Table 4 and the U.S. Standard Atmosphere of 1976, with a moisture burden given by the midlatitude average profile (see Appendix C, Fig. C-2).

The results of the computations are given in Table 4, where the various methods can be compared. The numerical method gives results for the wildland fires similar to those of the empirical method, but these do not necessarily represent reality either. The (vertical) rate of rise of many of the plumes was calculated as a few cm/s below the point of neutral buoyancy, so neglecting the effect of the (horizontal) 10 m/s windspeed is wrong.

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*Projecting the burning area below the surface to a "virtual origin" as suggested in Morton (1957) gives an origin farther below the surface than the plume height.

TABLE 4. PLUME RISE CALCULATIONS FOR THE FIRES OF TABLE 3

	Fire	Area Burning (m^2)	Power Q (MW)	Predicted Height of Plume Rise (km): Morton-T-T Eq. 1	Empir. (Chandler) Eq. 2 etc.	Numerical Model: Condenses	Numerical Model: Maximum
A.	Small Savana	500	25	2.2	1.5	0.8	*
B.	Small Forest Fire (litter)	500	50	2.6	2.0	0.8	*
C.	Intense Brush/ Crown Fire	5,000	750	5.1	6.5	1.4	7.7
D.	Slash Fire/ Land Clearing	50,000	5,000	7.6	8.6	2.3	8.5
E.	Tillamook	500,000	50,000	11.9	12.2	3.4	9.6
F.	Tacoa Oil Fire	10,000	750	2.3	2.1	1.7	7.9
G.	Meteotron	20,000	1,000	1.5	1.3 (USSt. Atm.)	1.9	5.0
					(wet winter day)	2.5	2.5
					(8 July 78 Meteotron atmosphere: water estimated, sultry range)		
						2.4	2.5
						2.2	2.45

*Plume saturated and went into an unsaturated state about 500 m higher, at a rise rate $\gtrsim$ 1 cm/s. Neutral density expected to occur at about 1.5 km, but model was not run above desaturation height.

Note that the methods differ markedly in their predictions of plume rise for the Tacoa oil fire, for which the empirical method of Chandler et al. was not designed.

The point here is that the misapplication of a theory may sometimes yield a believable result, but it may not represent reality. Thus, when such a theory is applied to a situation with which the user is unfamiliar, meaningless results may be obtained and yet go unrecognized.

2.3 A QUALITATIVE DISCUSSION OF THE FORMATION, SPREADING, AND DISAPPEARANCE OF A WATER CLOUD

The discussion of Section 2.2 points out that a large fire creates a significant combustion plume which takes a substantial amount of water vapor to stabilization at height h_s. A qualitative discussion of the formation, spreading, and disappearance of a water cloud may be based on the following assumptions.

(a) During plume rise, 1 to 10 kg H_2O/kg fuel is entrained and brought to stabilization.

(b) Stabilization occurs in the middle troposphere, which at midlatitudes is assumed to have 50 percent relative humidity (see, e.g., Appendix C, Fig. C-2).

(c) For a point source of tracer, if one describes mean wind dispersion in terms of turbulence, the horizontal mean cloud width is given in Fig. 4 as a function of travel time, where the range of curves I-III-IV is a measure of the variability of atmospheric turbulence. We assume a vertical cloud width $\sigma_z = 0.5$ km and for horizontal cloud width use the values of σ_y from Fig. 4 computed at t = 1 hour for curves I (minimum), III (mean), and IV (maximum) which are, respectively, 0.65, 7, and 60 km. The cloud volume for one hour of burning is

$$V = \sigma_y^2 \sigma_z . \qquad (5)$$

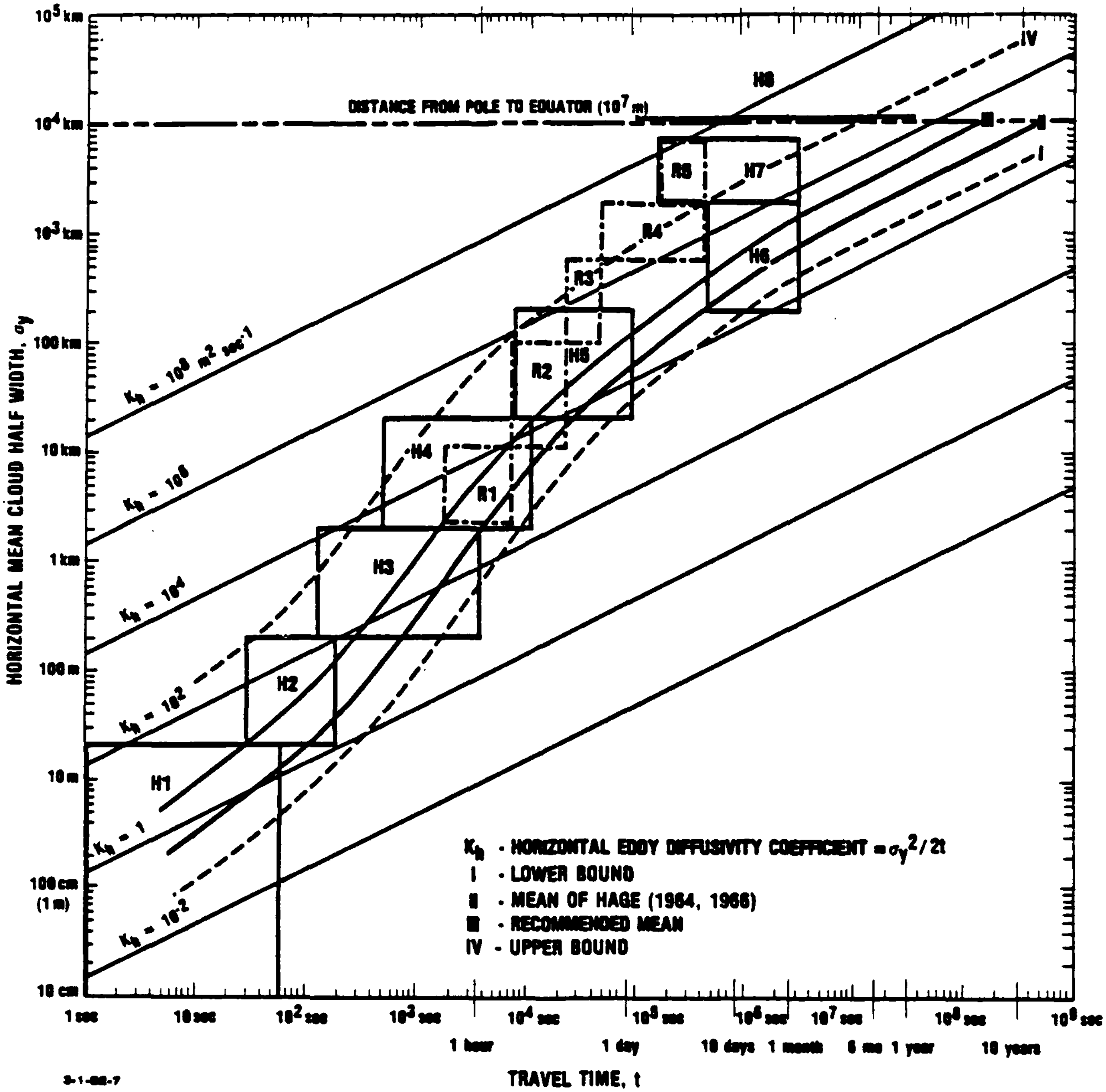

FIGURE 4. Horizontal dispersion as a function of travel time. The mean curves and bounds apply to atmospheric altitudes up to 20 to 25 km. Earlier estimate of Hage (1964), Hage et al. (1966) indicated slower spreading than do the more recent data. Thus, at present, the mean curve III with bounds I and IV is recommended as against Hage's mean curve II and bounds I and III.

Source: Bauer (1983).

Now for conditions A-D above, Table 5 lists whether or not water clouds are formed, and if they are, how long they remain before expansion takes them into a volume which is no longer saturated so that the cloud evaporates. We see that for violent atmospheric turbulence (curve IV) the cloud expansion is so rapid that condensation never occurs, while for minimal atmospheric turbulence (curve I) clouds are generally formed, and remain for times of 1 to 10 hours.

It is clear that the assumptions A, B, and C are only schematic, but they do lead to numbers that are not unreasonable. Referring back to Fig. 2, we see that the capping cumulus has a maximum dimension of order 20 km which, from Fig. 4 would suggest a mean lifetime of perhaps two hours for curve III or "average" atmospheric turbulence. This is certainly not inconsistent with the behavior of actual cumulus clouds which occur under relatively unstable conditions, i.e., between curves III and IV of Fig. 4.

2.4 LATE-TIME BEHAVIOR OF SMOKE

The present discussion deals with the generation of the smoke cloud, including the formation and disappearance of a capping cumulus in its first few hours. What happens after that?

The (black or gray) smoke plume left behind after the water cloud has evaporated is advected within an "air parcel". The motion of this parcel is approximately isentropic but the cloud absorbs solar energy during the daytime and in so doing gains some buoyancy, so that it rises more than it otherwise would (see, e.g., Bauer, 1984, Appendix E). (Note that the cooling due to thermal emission in the IR will be relatively small, as is the greenhouse effect due to the smoke (see, e.g., Bauer, 1984, Appendix C, McCartor et al., 1985). Thus, the air parcel will gain perhaps 90 percent of the absorbed solar energy, leading to a net increase in its potential temperature.)

TABLE 5. WATER PLUMES: FORMATION AND DISSIPATION

Combustion rate:	1000 tonnes fuel/hour				10,000 tonnes fuel/hour		
Stabilization height (km)	2.5				4.4		
Curve	I	III	IV		I	III	IV
σ_y(km)	0.65	7	70		0.65	7	70
Volume $\sigma_y \sigma_z$(km^3)	0.21	24.5	2450		0.21	24.5	2450
Mass of air (10^6 tonnes)							
(ρ_{air} = 0.96 kg/m^3)	0.20	23.5	2350	(ρ_{air} = 0.8 kg/m^3)	0.17	20	2000
Mass of ambient water (10^3 tonnes, 50% relative humidity)							
(ρ_w = 2.3 g/m^3)	0.50	54	5400	(ρ_w = 0.9 g/m^3)	0.19	22	2200
<u>Mass of transported water</u> (10^3 tonnes)							
Minimum: 1 kg/kg fuel		1				10	
Maximum: 10 kg/kg fuel		10				100	
<u>Minimum</u>: saturated to distance							
$\sigma_{y,min}$(km)	0.65	0.65	0.65		4.7	4.7	4.7
for time (hours)	0.1	no condensation			4.2	no condensation	
<u>Maximum</u>: saturated to distance							
$\sigma_{y,max}$(km)	2.9	2.9	2.9		15	15	15
for time (hours)	2.8	no condensation			12.5	2	no condensation

Eventually the smoke must be scavenged from the atmosphere, and there are at least three distinct mechanisms with possibly different time scales:

1. Immediate rainout leading to "black rain". This has been observed (e.g., in Dresden and Hiroshima in World War II bombing raids, and also in some forest fires). Calculations (e.g., Molenkamp, 1983) agree with observations which suggest that this process only occurs some 10 percent of the time and so removes less than this fraction of smoke on the average. Certainly the present discussion does not offer a mechanism for immediate rainout, though one can imagine that it might occur if a fairly fresh smoke plume encounters a parcel of moist, unstable air.
2. Wet or dry transport to the surface and subsequent removal. The time scale for this is one to three weeks for most non-reactive tracers in the troposphere (see, e.g., Pruppacher and Klett, 1978), somewhat less for reactive materials such as sulfuric and nitric acids. The aged smoke particles will presumably disappear as fast as the average "non-reactive tracer" since they will not be as hydrophobic as when they are fresh.
3. Heterogeneous chemical removal, e.g., by reaction with ozone or other reactive atmospheric material. Preliminary observations (deHaas et al., 1986, and Golden, 1986) suggest characteristic times of one to three months (with uncertainty by perhaps an order of magnitude up or down) for soot removal.

2.5 OPTICAL PROPERTIES OF SMOKE

As has been pointed out above, the mass of a capping cumulus or other cloud of entrained and condensed water is much greater than that of a late-time black or white/gray smoke plume, because the mass of water from both combustion and entrainment is several orders of magnitude greater than the mass of smoke. Note, however, that this condensed water will evaporate rather rapidly (see, e.g., Section 2.4) so that after some hours it will all be gone.

Thus, the climatic impact of the "Nuclear Winter" smoke cloud is largely that of the smoke, not of the condensed water. (Indeed, it is now considered that the net climatic impact of water clouds is rather small, in that the cooling due to the scattering of sunlight by the cloud roughly balances the greenhouse warming due to the absorption of earthshine (see, e.g., Cess et al., 1982).

Here we shall review the optical properties of water and smoke particles in both visible and infrared, distinguishing between smoke from oil and wood fires. For reference, Table 6 contains the complex refractive index of water and soot, as well as of some other atmospheric aerosols. Note that in the visible, soot is much more absorptive than water, whereas in the IR, especially for $\lambda \gtrsim 10$ μm, most materials have similar absorptivity N_2.

The smoke from oil fires looks black and is here assumed to be made up of soot, which is typically considered to be made up of very small particles (> 0.01 μm minimum dimension) which tend to clump together. Here these soot particles are treated as spheres of radius a, which are characterized by the Mie parameter q:

$$q = 2\pi \; a/\lambda \tag{6}$$

for light of wavelength λ. Here $q \ll 1$, i.e., we are in the <u>Rayleigh region</u> in which there is very little scattering, while the absorption cross section is proportional to the volume of the particle divided by the wavelength of light. Explicitly (cf. Van de Hulst, 1957),

TABLE 6. REFRACTIVE INDEX FOR VARIOUS AEROSOL COMPONENTS

WAVELENGTH (MICRONS)	WATER SOLUBLE		DUST-LIKE		SOOT		SEA SALT		WATER	
.2000	1.530	-7.00E-02	1.530	-7.00E-02	1.500	-.350	1.510	-1.00E-04	1.396	-1.10E-07
.2500	1.530	-3.00E-02	1.530	-3.00E-02	1.620	-.450	1.510	-5.00E-06	1.362	-3.35E-08
.3000	1.530	-8.00E-03	1.530	-8.00E-03	1.740	-.470	1.510	-2.00E-06	1.349	-1.60E-08
.3371	1.530	-5.00E-03	1.530	-8.00E-03	1.750	-.470	1.510	-4.00E-07	1.345	-8.45E-09
.4000	1.530	-5.00E-03	1.530	-8.00E-03	1.750	-.460	1.500	-3.00E-08	1.339	-1.86E-09
.4880	1.530	-5.00E-03	1.530	-8.00E-03	1.750	-.450	1.500	-2.00E-08	1.335	-9.69E-10
.5145	1.530	-5.00E-03	1.530	-8.00E-03	1.750	-.450	1.500	-1.00E-08	1.334	-1.10E-09
.5500	1.530	-6.00E-03	1.530	-8.00E-03	1.750	-.440	1.500	-1.00E-08	1.333	-1.96E-09
.6328	1.530	-6.00E-03	1.530	-8.00E-03	1.750	-.430	1.490	-2.00E-08	1.332	-1.46E-08
.6943	1.530	-7.00E-03	1.530	-8.00E-03	1.750	-.430	1.490	-1.00E-07	1.331	-3.05E-08
.8600	1.520	-1.20E-02	1.520	-8.00E-03	1.750	-.430	1.480	-3.00E-06	1.329	-3.29E-07
1.0600	1.520	-1.70E-02	1.520	-8.00E-03	1.750	-.440	1.470	-2.00E-04	1.326	-4.18E-06
1.3000	1.510	-2.00E-02	1.460	-8.00E-03	1.760	-.450	1.470	-4.00E-04	1.323	-3.69E-05
1.5360	1.510	-2.30E-02	1.400	-8.00E-03	1.770	-.460	1.460	-6.00E-04	1.318	-9.97E-05
1.8000	1.460	-1.70E-02	1.330	-8.00E-03	1.790	-.480	1.450	-8.00E-04	1.312	-1.15E-04
2.0000	1.420	-8.00E-03	1.260	-8.00E-03	1.800	-.490	1.450	-1.00E-03	1.306	-1.10E-03
2.2500	1.420	-1.00E-02	1.220	-9.00E-03	1.810	-.500	1.440	-2.00E-03	1.292	-3.90E-04
2.5000	1.420	-1.20E-02	1.180	-9.00E-03	1.820	-.510	1.430	-4.00E-03	1.261	-1.74E-03
2.7000	1.400	-5.50E-02	1.180	-1.33E-02	1.830	-.520	1.400	-7.00E-03	1.188	-1.90E-02
3.0000	1.420	-2.20E-02	1.160	-1.20E-02	1.840	-.540	1.610	-1.00E-02	1.371	-.272
3.2000	1.430	-8.00E-03	1.220	-1.00E-02	1.860	-.540	1.490	-3.00E-03	1.478	-9.24E-02
3.3923	1.430	-7.00E-03	1.260	-1.30E-02	1.870	-.550	1.480	-2.00E-03	1.422	-2.04E-02
3.5000	1.450	-5.00E-03	1.280	-1.16E-02	1.880	-.560	1.480	-1.60E-03	1.400	-9.40E-03
3.7500	1.452	-4.00E-03	1.270	-1.10E-02	1.900	-.570	1.470	-1.40E-03	1.369	-3.50E-03
4.0000	1.455	-5.00E-03	1.260	-1.20E-02	1.920	-.580	1.480	-1.40E-03	1.351	-4.60E-03
4.5000	1.460	-1.30E-02	1.260	-1.40E-02	1.940	-.590	1.490	-1.40E-03	1.332	-1.34E-02
5.0000	1.450	-1.20E-02	1.250	-1.60E-02	1.970	-.600	1.470	-2.50E-03	1.325	-1.24E-02
5.5000	1.440	-1.80E-02	1.220	-2.10E-02	1.990	-.610	1.420	-3.60E-03	1.298	-1.16E-02
6.0000	1.410	-2.30E-02	1.150	-3.70E-02	2.020	-.620	1.410	-1.10E-02	1.265	-.107
6.2000	1.430	-2.70E-02	1.140	-3.90E-02	2.030	-.625	1.600	-2.20E-02	1.363	-8.80E-02
6.5000	1.460	-3.30E-02	1.130	-4.20E-02	2.040	-.630	1.460	-5.00E-03	1.339	-3.92E-02
7.2000	1.400	-7.00E-02	1.400	-5.50E-02	2.066	-.640	1.420	-7.00E-03	1.312	-3.21E-02
7.9000	1.200	-6.50E-02	1.150	-4.00E-02	2.120	-.670	1.400	-1.30E-02	1.294	-3.39E-02
8.2000	1.010	-.100	1.130	-7.40E-02	2.130	-.680	1.420	-2.00E-02	1.286	-3.51E-02
8.5000	1.300	-.215	1.300	-9.00E-02	2.156	-.690	1.480	-2.60E-02	1.278	-3.67E-02
8.7000	2.400	-.290	1.400	-.100	2.160	-.690	1.600	-3.00E-02	1.272	-3.79E-02
9.0000	2.560	-.370	1.700	-.140	2.170	-.700	1.650	-2.80E-02	1.262	-3.99E-02
9.2000	2.200	-.420	1.720	-.150	2.166	-.700	1.610	-2.60E-02	1.255	-4.15E-02
9.5000	1.950	-.160	1.730	-.162	2.190	-.710	1.580	-1.80E-02	1.243	-4.44E-02
9.8000	1.870	-9.50E-02	1.740	-.162	2.200	-.715	1.560	-1.60E-02	1.229	-4.79E-02
10.0000	1.820	-9.00E-02	1.750	-.162	2.210	-.720	1.546	-1.50E-02	1.218	-5.08E-02
10.5910	1.760	-7.00E-02	1.620	-.120	2.220	-.730	1.500	-1.40E-02	1.179	-6.74E-02
11.0000	1.720	-5.00E-02	1.620	-.105	2.210	-.733	1.480	-1.40E-02	1.153	-9.68E-02
11.5030	1.673	-4.70E-02	1.590	-.100	2.246	-.740	1.480	-1.40E-02	1.126	-.142
12.5000	1.620	-5.30E-02	1.510	-9.00E-02	2.270	-.750	1.420	-1.60E-02	1.123	-.259
13.0000	1.620	-5.50E-02	1.470	-.100	2.280	-.763	1.410	-1.80E-02	1.146	-.305
14.0000	1.560	-7.30E-02	1.520	-8.50E-02	2.310	-.775	1.416	-2.30E-02	1.210	-.370
14.8000	1.440	-.100	1.570	-.100	2.330	-.790	1.430	-3.00E-02	1.258	-.396
15.0000	1.420	-.200	1.570	-.100	2.330	-.790	1.450	-3.50E-02	1.276	-.402
16.4000	1.750	-.160	1.600	-.100	2.360	-.810	1.560	-9.00E-02	1.346	-.427
17.2000	2.080	-.240	1.630	-.100	2.380	-.820	1.740	-.120	1.386	-.429
18.0000	1.980	-.180	1.640	-.115	2.400	-.825	1.780	-.136	1.423	-.426
18.5000	1.853	-.170	1.640	-.120	2.410	-.830	1.770	-.135	1.443	-.421
20.0000	2.120	-.220	1.680	-.220	2.436	-.840	1.760	-.152	1.480	-.393
21.3000	2.060	-.230	1.770	-.280	2.460	-.860	1.760	-.165	1.491	-.379
22.5000	2.000	-.240	1.900	-.280	2.480	-.870	1.760	-.180	1.506	-.370
25.0000	1.880	-.280	1.970	-.240	2.510	-.890	1.780	-.205	1.531	-.356
27.9000	1.840	-.290	1.890	-.320	2.546	-.910	1.770	-.275	1.549	-.339
30.0000	1.820	-.300	1.800	-.420	2.570	-.933	1.770	-.300	1.551	-.328
35.0000	1.920	-.400	1.900	-.500	2.630	-.970	1.760	-.500	1.532	-.336
40.0000	1.860	-.500	2.100	-.600	2.690	-1.000	1.740	-1.000	1.519	-.385

Source: Shettle and Fenn (1979)

$$\sigma_{sca} = (32/27)\ \pi\ a^2\ q^4\ (N_1 - 1)^2 \qquad (a)$$

$$\sigma_{abs} = (8/3)\ \pi\ a^2\ qN_2, \qquad (b) \qquad (7)$$

where N_1 and N_2 are, respectively, the real and imaginary parts of the complex refractive index.

The smoke from oil fires is quite variable in both amount and characteristics depending on the characteristics of the fires (cf, (e.g., presentations at the 20th Symposium (International) on Combustion, Ann Arbor, MI, August 1984). It often contains a significant number of large particles, which scatter as much as they absorb. Note however:

(a) the assumption that much of the absorption comes from small particles for which Eq. (7) holds may still be useful if the electric field vector of the incident radiation is parallel to the smallest dimension of the soot particles.

(b) while a capping cloud exists, one will tend to see this rather than the smoke cloud because of its much larger mass (see, e.g., Fig. 2).

Fraser et al. (1986) have analyzed visible satellite imagery (from GOES) of the July 1982 Yukon forest fires over the Great Lakes, over Chesapeake Bay, and over the North Atlantic. Because of the long transit time (1 to 3 days) this smoke has been aged so that any capping cumulus clouds will presumably have evaporated. Fraser et al. (1986) find:

(a) maximum optical thickness ~ 1.6 - 2 in vertical viewing

(b) single scattering albedo ω, defined as

$$\omega = \sigma_{sca} / (\sigma_{sca} + \sigma_{abs}) \qquad (8)$$

in the range 0.92 - 0.98, i.e., extinction is due mainly to scattering rather than to absorption

(c) mean particle size $a \sim 0.3$ μm, so that the Mie parameter $q = 2\pi a/\lambda \sim 2$ in the visible, which indicates that scattering can be significant (if $q << 1$, $\sigma_{sca} \propto q^4$, which is very small).

It must be stressed that the results of Fraser et al. have been obtained by an as-yet-unvalidated method. Nevertheless, they do suggest that a forest fire of the Yukon (boreal) type produces smoke which is largely scattering rather than absorptive in the visible--and GOES imagery of the visible plume over the North Atlantic on 2 August 1982 is consistent with that result.

One question which must be addressed is the following: can one tell "by eye" whether a given cloud is largely absorptive/("black") or scattering/("white")? The answer is somewhat subtle. Table 7 gives the effective hemispheric reflectivity for optically thick clouds as a function of single scattering albedo or the ratio of absorption to scattering cross section. The reflectivity clearly depends on the angle of illumination: for near-normal illumination the reflectance is smaller than for near-tangential (glancing angle) illumination. However, even for $\sigma_{abs}/\sigma_{sca} \sim 0.15$ to 0.20 the hemispherical reflectance for near-normal illumination is of order 0.1 (for tangential illumination it would be ~ 0.25). Thus, even if a large part of the extinction is due to scattering, the plume or cloud may still look dark gray.

This raises a major unknown--what is smoke? Is it largely an absorbing medium made up of graphitic soot--particles so small that they do not scatter much, i.e., $q = 2\pi a/\lambda \leqslant 1$, e.g., $a \sim 0.01$ μm--or in part larger scattering particles for which $q \gtrsim 1$, i.e., $a \gtrsim 0.09$ μm for $\lambda \lesssim 0.55$ μm. The question is significant because if $q << 1$, $\sigma_{sca} \sim q^4 \pi a^2 \rightarrow 0$ so that $\sigma_{ext} = \sigma_{sca} + \sigma_{abs} \approx \sigma_{abs}$ from Eq. (7), and the effective optical thickness X_e of a cloud of geometrical thickness L and mass loading M (g/m^3) is

TABLE 7. HEMISPHERIC REFLECTANCE FOR OPTICALLY THICK CLOUDS AS A FUNCTION OF SINGLE SCATTERING ALBEDO ω_o, FOR NEAR-NORMAL AND NEAR-TANGENTIAL ILLUMINATION

	Single scattering Albedo $\omega_o = \sigma_{sca}/(\sigma_{abs} + \sigma_{sca})$			
ω_o	1.0	0.9	0.8	0.0
Ratio of absorption to scattering cross section, $\sigma_{abs}/\sigma_{sca}$	0.0	0.11	0.25	∞
Hemispheric Reflectance				
(near-normal illumination)	1.0	0.13 to 0.16	0.06 to 0.08	0.00
(illumination 5° above tangent)	> 0.95	0.44	0.30	0.00

Source: Calculations by M. King (NASA/GSFC), kindly provided by R.S. Fraser

$$X_e = n\,\sigma_{ext}\,L \tag{9}$$

$$= (3\pi/2)\,N_2\,ML\,/\,\lambda\rho \qquad \text{for} \quad q \ll 1 \tag{10}$$

where n = number density of particles of density = $M/(4\pi\rho a^3/3)$. By contrast, if $q \gtrsim 1$, $\sigma_{ext} \sim c\pi a^2$ ($c \sim 2$) so that

$$X_e = 3cML/4a\rho \qquad \text{for } q \gtrsim 1 \tag{11}$$

so that if $q \gtrsim 1$, larger particles produce a significantly smaller optical thickness and thus extinction, cooling, etc., than do smaller particles.

Evidently, either absorbing or scattering particles--or any combination thereof--can produce surface cooling, but the numerical magnitude of the effect may depend critically on some details of what the smoke actually is.

2.6 CLIMATIC EFFECTS OF SMOKE

(a) The climatic impact of water/ice clouds has been studied by many people, in particular by Cess et al. (1982). The key question is the relative importance of cooling due to reduction in incoming solar radiation ("albedo effect") and the reduction in outgoing earthshine ("IR radiation"). The conclusion is that these two relatively large effects almost balance, so that there is either a very small net heating or a very small net cooling--but different data give different signs of the net effect. Whether the clouds are high or low can also be important in this regard.

(b) As far as the absorption from soot is concerned we assume that Mie parameter q of Eq. (6) is very much less than one in the visible as well as in the LWIR.

Thus, the optical thickness in the LWIR, X(LW), is very much smaller than that in the visible, X(VIS), because

$$\frac{X(LW)}{X(VIS)} = \frac{q(LW)}{q(VIS} \times \frac{N_2(LW)}{N_2(VIS)},$$

where N_2 = imaginary part of complex refractive index; typically $N_2(LW)/N_2(VIS) \sim 3$ to 10 whereas $q(LW)/q(VIS) \approx 0.05$. Accordingly, the primary effect of soot/smoke particles is cooling due to extinction of solar radiation rather than greenhouse warming.

(c) The climatic effect of grey/white smoke is harder to estimate. In the visible, solar radiation will be extincted by scattering rather than by absorption, while the greenhouse warming in the LWIR will probably be small. However, the quantitative estimate of net cooling due to gray/white clouds will presumably depend on details of particle size and absorptivity (see, e.g., Bartky and Bauer, 1966, and Bartky, 1968).

3. DISCUSSION

This analysis demonstrates how the initial plume rise to stabilization depends on the intensity of the fire and also on atmospheric conditions: a moist lower atmosphere leads to an enhanced plume rise and sometimes to the formation of a capping cumulus cloud which is, however, relatively short-lived (to several hours--see Fig. 2 or Table 5). Because of this short lifetime, the climatic impact of the capping cumulus cloud is small.

However, after the capping cumulus or other water cloud evaporates due to expansion into the dry atmosphere, the residual smoke plume continues to rise under its solar-induced buoyancy (cf, e.g., Bauer, 1984, p. E-4, especially Eq. (4), also Knox et al., 1986, p. 20), so that the final plume rise height will tend to be specified by its late-time behavior rather than by its initial injection height. Note that the "Nuclear Winter" cooling from a high-altitude smoke plume is significantly greater than that from a low-altitude smoke plume (e.g., compare the results of Ramaswamy and Kiehl, 1985, Fig. 17), which after 20 days show a cooling of 33°C for the high-altitude (constant density) profile D as compared to 23°C cooling for the lower-altitude (constant mixing ratio) profile M. In addition, the residence time of material in the atmosphere is greater for higher altitudes, so that--other things being equal--the higher-altitude smoke distribution D will remain longer than the lower-altitude profile M.

By looking at Fig. 2 or at any instantaneous photograph of a smoke plume, one notes that the smoke on a given occasion is not uniformly distributed in a horizontal plane, although the distribution averaged over many different smoke injections will be uniform. It can be shown that if a given amount of smoke is distributed uniformly, its total extinction of the underlying surface will have a maximum value. If the distribution is non-uniform ("lumpy"), more radiant energy will penetate the cloud to give less net cooling. Appendix D gives a simple example for a plume of optical thickness X and transmission e^{-X} (i.e., absorption only): if X ~ 3 to 10, the effective extinction can be reduced by a factor of 1.5 to 8 if the thick and thin plumes differ in optical thickness by a factor of 2 to 16. This is clearly a very simple example: a more refined calculation will give different numerical results, but the most effective way to solve this problem is experimentally, by studying the transmission through actual smoke plumes.

An additional factor of importance is provided by the optical properties of the smoke, in particular by the ratio of absorption to scattering, where absorbing (black, oil) smoke tends to give less transmission and thus more cooling than does scattering (white, wood) smoke.

From the original photo on which Fig. 2 is based, one can see that during land clearing in Brazil in August 1984 the smoke plume remaining after the capping cloud over the large fire evaporates is white or light gray, not black, i.e., largely scattering rather than absorbing. This is indeed characteristic of smoke from wood fires (forest or agricultural). In terms of the single scattering albedo

$$\omega = \sigma_{sca} / \sigma_{ext} , \tag{12}$$

where

$$\sigma_{ext} = \sigma_{sca} + \sigma_{abs} . \tag{13}$$

Fraser et al. (1986) find ω = 0.92 - 0.98 for smoke from the Yukon fires of July 1982 after 1 to 3 days' travel, using an as-yet-unvalidatd method of analyzing visible GOES satellite data. Ginsburg and Golitsyn (1986) quote ω = 0.9 for representative fires in the USSR.

By contrast, Roessler and Faxvog (1981) quote $\omega \sim 0.15$ for soot, i.e., the highly absorptive smoke from oil fires. (Such low values are supported qualitatively from observations on oil pool fires--B. Zak, Sandia National Laboratory, private communication.)

From an analysis of the available fuel in a "representative" city, Knox et al. (1986, p. 19) suggest that 15 to 20 percent of fuel consists of oil or oil-derived material, with the remainder being wood or wood-derived. If the wood-derived smoke has $\omega \sim$ 0.9 to 0.95 and if the oil has no scattering, i.e., $\omega = 0.0$, and all materials have the same smoke emission index, this gives $\omega \sim 0.7$ to 0.8 for a major urban fire.

The effect of this contribution of scattering to extinction is to increase the transmission through a cloud of given extinction optical thickness X_e:

$$X_e = n\,\sigma_{ext}\,L\ , \tag{14}$$

where n = number of particles per unit volume and L = geometrical cloud thickness. Table 8 gives the transmission coefficient $t(X;\omega)$ for a plane wave incident normally on a uniform medium as a function of optical thickness X and single-scattering albedo. The results show that for a given optical thickness X absorbers (ω small) transmit less radiant energy than do scatterers (ω close to 1), so that the effective "Nuclear Winter" cooling due to absorbing (black, oil) smoke is greater than that due to scattering (white, wood) smoke. The calculations are given for two simple models A (isotropic) and B (forward + backward scattering only) to demonstrate these qualitative characteristics: the numerical values, of course, depend on the particular model adopted.

TABLE 8. TRANSMITTANCE IN VISIBLE AS A FUNCTION OF SINGLE SCATTERING ALBEDO ω AND EXTINCTION OPTICAL THICKNESS (X_e), FOR TWO DIFFERENT MODELS A AND B[1]

ω	Source	Transmittance ($t_A;t_B$) as a function of extinction optical thickness X_e		
		X_e = 1	3	10
0.00	Perfect absorbers[2]	0.37; 0.37	0.05; 0.05	4.5×10^{-5}; 4.5×10^{-5}
0.15	Soot[3]	0.40; 0.42	0.063; 0.075	9.9×10^{-5}; 1.8×10^{-4}
0.4	Smoke: $\bar{a}$ = 0.1 to 1 μm, lower bound[4]	0.46; 0.52	0.096; 0.15	0.0004; 0.0017
0.7	Smoke: $\bar{a}$ = 0.1 to 1 μm, upper bound[4]	0.54; 0.69	0.18; 0.33	0.0038; 0.026
0.92	Aged forest fire smoke lower bound[5]	0.63; 0.85	0.32; 0.61	0.05; 0.55
0.98	Aged forest fire smoke upper bound[5]	0.66; 0.89	0.38; 0.73	0.12; 0.40
1.00	Perfect scatterers--no absorption	0.67; (0.9)	0.40; (0.8)	0.17; (0.5)

1 Model A assumes isotropic scattering (see, e.g., Bartky and Bauer, 1966, Model 2). Model B assumes a combination of strictly forward and strictly backward scattering, with a ratio of forward to backward scattering of 9:1 (see Van de Hulst, 1980, p. 489f, asymmetry g = 0.8).

Both models assume propagation normal to the cloud.

2 E.g., Ramaswamy and Kiehl (1985), $\bar{a}$ = 0.01 μm.

3 Roessler and Faxvog (1981).

4 Ramaswamy and Kiehl (1985).

5 Fraser et al. (1986).

4. APPLICATION TO THE GLOBAL EFFECTS/NUCLEAR WINTER PROBLEM

The preceding discussion pointed out the following:

(a) For the climatic cooling, the initial plume rise may well be less important than the long-term motion due to solar-induced buoyancy and other atmospheric motions. (Ramaswamy and Kiehl, 1985, indicate a possible variability by a factor of 1.5 between a "constant density" and a "constant mixing ratio" model.)

(b) On any given occasion, the smoke plume will be quite nonuniform. The result will be to reduce the effective cooling by a significant factor (the simple model of Appendix D suggests a factor of 1.5 to 8, but this is highly uncertain).

(c) Since--for a given optical depth--absorption is much more effective than scattering in reducing transmission and thus producing cooling, the late-time optical properties of the smoke are crucial. (Table 8 suggests that a variability by a factor of 2 to 5 is likely for transmission between different models that have been used.)

How can these effects be studied?

(a) Perhaps the best example of long-term, solar-induced buoyancy is provided by Arctic Haze. As an example, the AGASP program (see, e.g., Schnell, 1984) demonstrates that the plume of the Norilsk copper-nickel smelter could, on occasion, be followed for 10 days from the surface source in Siberia to layers near 3 km over Alaska (see, e.g., Harris, 1984; Iverson, 1984; Ottar and Pacyna, 1984; and Radke et al., 1984).

(b) Smoke nonuniformity can be studied by quantitative photographic or video techniques by looking at plumes; the plumes from larger sources can normally be studied for longer times than those from smaller sources, depending on atmospheric conditions.

(c) The effective climatic cooling will be determined by late-time optical properties of smoke, and this requires large sources which can be followed for long times. For wood/forest fires, the best (if unvalidated) method is that used by Fraser et al. (1986) for from 1 to 3 days. Sooty smoke from oil fires may react with ozone at very long times (months--cf. e.g., de Haas et al., 1986, and Golden, 1986); the best approach right now is to use the plume from large oil pool fires at Sandia National Laboratory, which can be tracked with an aircraft for several hours (Zak et al., 1986).

5. RECOMMENDATIONS

1. Use Arctic Haze data to study long-term plume rise by solar-induced buoyancy and transport.
2. Use data from large fires to study the evolution of the late-time plume nonuniformity which will affect the transmittance of solar radiation and thus the long-term climatic cooling.
3. Validate the method of Fraser et al. (1986) for studying the late-time (1- to 3-day) optical properties of smoke from wood fires using weather satellite imagery.
4. Use the large Sandia National Laboratory oil pool fires as a source to study late-time (1- to 6-hour) optical properties of sooty oil smoke in a dry atmosphere.

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APPENDIX A

TASK ORDER

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON DC 20301

RESEARCH AND ENGINEERING

9 February 1984

TASK ORDER
NO. MDA903 84 C 0031: T-4-237

TITLE: Atmospheric Injection and Scavenging of Smoke Particles from Fires

1. This task is for work to be performed by the Institute for Defense Analyses for the Defense Nuclear Agency.

2. BACKGROUND:

The current concern of major climatic cooling arising from a nuclear exchange is based largely on the scenario that nuclear detonations will ignite large fires. These fires produce a large quantity of fine smoke particles, which - when carried sufficiently high in the atmosphere - are claimed to produce cooling at the earth's surface. The altitude of the smoke cloud is alleged to determine whether cooling or warming occurs, while the rate of removal of the smoke particles will determine the duration of the climatic effects. An evaluation of the quantities of smoke particles, the rise height, and the scavenging rate is needed as a first step in determining the credibility of this scenario. To do so, data on different types of fires (urban, forest, oil, etc.) and on removal mechanisms and rates will be examined.

3. OBJECTIVE AND SCOPE:

To evaluate the magnitude of particulate injection, the rise height, and the rate of removal of smoke particles put into the atmosphere as a consequence of large-scale fires as posited to result from a massive nuclear exchange. The work will review current knowledge and uncertainties and make recommendations on how the uncertainties may be reduced.

4. SCHEDULE:

This effort will begin 1 January 1984. A draft document will be delivered by 30 September 1984, and a final version 90 days thereafter. Memoranda and briefings will be given as significant portions of the effort are completed.

5. TECHNICAL COGNIZANCE:

Technical cognizance for this task is assigned to the Director, Radiation Directorate, Defense Nuclear Agency, Attn: RAAE.

6. FUNDING:

The expenditure of $74,000 of FY 1984 funds is authorized for this task.

7. SPECIFIC ADMINISTRATIVE INSTRUCTIONS:

a. If at any time during the course of this task IDA identifies the need for changes in this task, such as additional resources, schedule modification, changes to emphasis of effort or scope, etc., as set forth in the above paragraphs, a report with appropriate recommendations will be submitted in accordance with the terms of the IDA/WSEG Memorandum of Understanding of 12 March 1975 (and its successor) as applicable to the Director, DoD-IDA Management Office, OUSDRE, with a copy to the sponsor or his project officer, as appropriate. Changes in this task will be made only with the approval of appropriate cognizant DoD officials.

b. This task will be conducted under Industrial Security Procedures in the IDA area. If certain portions of the task require the use of sensitive information which must be controlled under military security, the DoD-IDA Management Office will provide supervised working areas in which work will be performed under military security control.

c. The termination date, the date after which no further costs will be incurred against the contract, for this task is 7 January 1985; unless changed by a written amendment to this task order.

d. A "need to know" is hereby established in connection with this task. Specifically, authority is granted to IDA to request, in my name, classified and unclassified documents and publications needed to accomplish this task and to verify, using my name, the "need to know" with respect to access to classified information needed to complete this task. Further, IDA authority to request documents and publications and to verify "need to know" with respect to security clearances is restricted (1) to IDA members assigned in writing to work on this task and (2), to the duration of this task, as specified in the task order.

T. L. RICKETTS
Colonel USA
Director
DoD-IDA Management Office

ACCEPTED:

A. J. GOODPASTER
General, U.S. Army (Ret.)
President, Institute for Defense Analyses

DATE: February 17, 1984

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON DC 20301

12 April 1985

RESEARCH AND ENGINEERING

TASK ORDER
NO. MDA903 84 C 0031: T-4-237
AMENDMENT NO. 1

TITLE: Atmospheric Injection and Scavenging of Smoke Particles from Fires

1. This task amendment is to extend work initiated under this task. Paragraphs 2, 3, 4, 6, and 8 are changed as follows:

2. BACKGROUND: Add:

"Task T-4-237 reviewed how much smoke is generated per unit area by urban and forest fires, and some critical aspects of atmospheric injection. It indicated the significance of meteorological variability, and how a study of forest fires can help to indicate what happens, in particular the effective smoke injection altitude and rate of disappearance.

Overall, the "Nuclear Winter" scenario has not been shown to be physically impossible, and thus it is appropriate to continue investigating all relevant aspects of the scenario with emphasis on actual physical phenomena which simulate different aspects of Nuclear Winter. One phase which has not been investigated in detail is how smoke is dispersed from its originating fires, near the ground, to the globally uniform distribution throughout the troposphere which is used in climate models as a basis for the predictions of a very large cooling. It is known that large-scale smoke and smog plumes travel over large distances, both horizontally and vertically, and here a study of forest fires and of arctic haze provides an opportunity to study the long-range transport and disappearance of the smoke, in particular soot.

3. OBJECTIVE AND SCOPE: Add:

"Work under Amendment 1 will use available data on forest fires, arctic haze, and other relevant phenomena which provide partial simulations for the Nuclear Winter scenario with the objectives of:

a. Bounding the effects

b. Providing a baseline for computer models of cloud spreading

c. Providing input information for climate models

Ongoing experimental and analytical work at NASA, NOA etc., will be used and extended as feasible, and recommendati on further work will be made."

4. SCHEDULE: Add:

"This effort under Amendment 1 will begin on 1 Decembe 1984. A draft document will be delivered by 30 September 198 and a draft final version 90 days thereafter. Memoranda and briefings will be given as significant portions of the effort are completed."

6. FUNDING: Add:

"The expenditure of $125,000 of FY 1985 funds is authorized to continue work on this task, as amended."

8. SPECIFIC ADMINISTRATIVE INSTRUCTIONS: Replace subparagraph c. with the following:

"c. The termination date, the date after which no furth costs will be incurred against the contract, for this task is December 1985."

T. L. Ricketts

T. L. RICKETTS
Colonel USA
Director
DoD-IDA Management Office

ACCEPTED: A. J. Goodpaster
A. J. GOODPASTER
General, U. S. Army (Ret.)
President, Institute for Defense Analyses

DATE: May 13, 1985

IDA
SCIENCE AND TECHNOLOGY DIVISION

INSTITUTE FOR DEFENSE ANALYSES
1801 N. Beauregard Street, Alexandria, Virginia 22311 • Telephone (703) 845-2000

January 14, 1986

MEMORANDUM FOR THE RECORD

SUBJECT: Task Order T-4-237, Amendment 1, Atmospheric Injection and Smoke Particles from Fires

In accordance with previous discussions, it is agreed that the final work on this Amendment, on black and white clouds from oil fires and implications for nuclear winter, will be delayed at no cost to the government until 1 August 1986. At that time, a draft report will be furnished with a proposed distribution list. DNA (RAAE) will return comments on the report, including approval of classification and approved distribution list, within three months thereafter. The report will be published by IDA in final form three months after receipt of sponsor's comments. Printing and distribution will be made when an approved distribution list is furnished to IDA, using resources provided by the task.

Robert E. Roberts
Director
Science and Technology Division
Institute for Defense Analyses

Leon A. Wittwer
Program Manager
Atmospheric Effects Division
Defense Nuclear Agency

APPENDIX B

SUMMARY OF IDA MEMORANDUM REPORT M-116

APPENDIX B

SUMMARY OF IDA MEMORANDUM REPORT M-116

This paper suggests a reason and a means to study large-scale natural and urban/industrial fires. Very large fires--both forest/agricultural and urban/industrial--provide a significant, if partial simulation for the urban fire scenario depicted as playing a role in the Nuclear Winter hypothesis. Only the largest naturally occurring fires provide the large-scale atmospheric smoke injections and perturbations that can be traced over long times (hours to days). Such fires occur only very rarely (fortunately), and thus they have to be treated as <u>experiments of opportunity</u>, i.e., to be studied when they occur, using observations from existing operational sensors. Large-scale/long-time current phenomena are best studied using earth/atmosphere observation satellites. Weather satellites provide global coverage with frequently updated imagery, but of relatively poor resolution (> 1 km)*.

To extract useful information from such experiments of opportunity calls for pre-planning. As an initial phase, a workshop involving experts within DOD, NOAA and NASA was held at IDA on 1 May 1985. Its product - a concept document on experiments of opportunity for Nuclear Winter - is reproduced here as Part I. It concluded that when an appropriate fire is reported, an ad hoc panel should be alerted to arrange in real time for all relevant satellite and other data to be taken and retained for later analysis. The panel and the procedure for

*"Regular" earth observation satellites such as LANDSAT and SPOT provide much higher resolution (20 to 80 m), but the typical 18-day revisit time for any point on the globe means that there is unlikely to be imagery of the (rare) events under consideration here.

alerting the panel and arranging for data collection must be established in advance, and checked out with a test exercise.

In the Nuclear Winter scenario, most smoke is now considered to be due to urban/industrial fires rather than to forest fires because of the total mass of material burned and thus the smoke generated. Cities and industrial complexes have high value and are designed to minimize the risk of devastating fires. By comparison, forests have a relatively low value per unit area. Thus, it is not surprising that large forest and agricultural fires are larger than even the largest industrial fires. Table B-1 shows some representative large fires that occurred in the 1970-1984 time frame. The industrial/urban fires are chosen from among the 20-odd largest such in the Americas over this time period; slash-and-burn occurs each year just before the planting season in Latin America, while a 10^6 hectare (2.5 million acre) boreal forest fire occurs in Yukon, Alaska or Siberia at least every 10 to 20 years.

From Table B-1 the question arises, how small a fire can be observed using weather satellite imagery. Part II of IDA Memorandum Report M-116 entitled "Remote Sensing of Smoke Plumes in the Visible: How Small a Plume/Fire Can One Expect to Detect?" addresses this question. After a parametric discussion of how a fire is detected using current satellite imagery, the example of the large oil fire that occurred on 20-22 December 1982 at Tacoa, Venezuela is discussed. Figure B-1 shows the early morning (7.08 a.m. LT) high resolution (1 km) NOAA-6 image on 20 December 1982; the plume over Caracas, Venezuela is due to this fire. Figure B-2 shows the afternoon (2.42 p.m.) low resolution (2 km) NOAA-7 image on the same day. Here the smoke plume cannot be seen, possibly because it has dissipated during the seven-hour interval, but mainly because of the typically heavy cumulus cloud buildup in the afternoon,

TABLE B-1. TENTATIVE ESTIMATES FOR SMOKE GENERATION BY LARGE FIRES

Fire	Fuel Burned (tonnes)	Time of Burning (days)	Smoke Fraction	Smoke Generation Rate (tonnes/day)
Lynn, MA: Urban	200,000; "wood"	2	3%	3,000
Anaheim, CA: Brush	520,000; "wood"	7	3%	2,200
Tacoa, Venezuela	40,000; oil	3	5%	670
Winchester, VA	200,000; rubber	90	10%	220
Slash and Burn: 1000 ha/day	10,000/day; wood	1	3%	300
10^6 ha forest	2×10^7; "wood"	30	3%	20,000

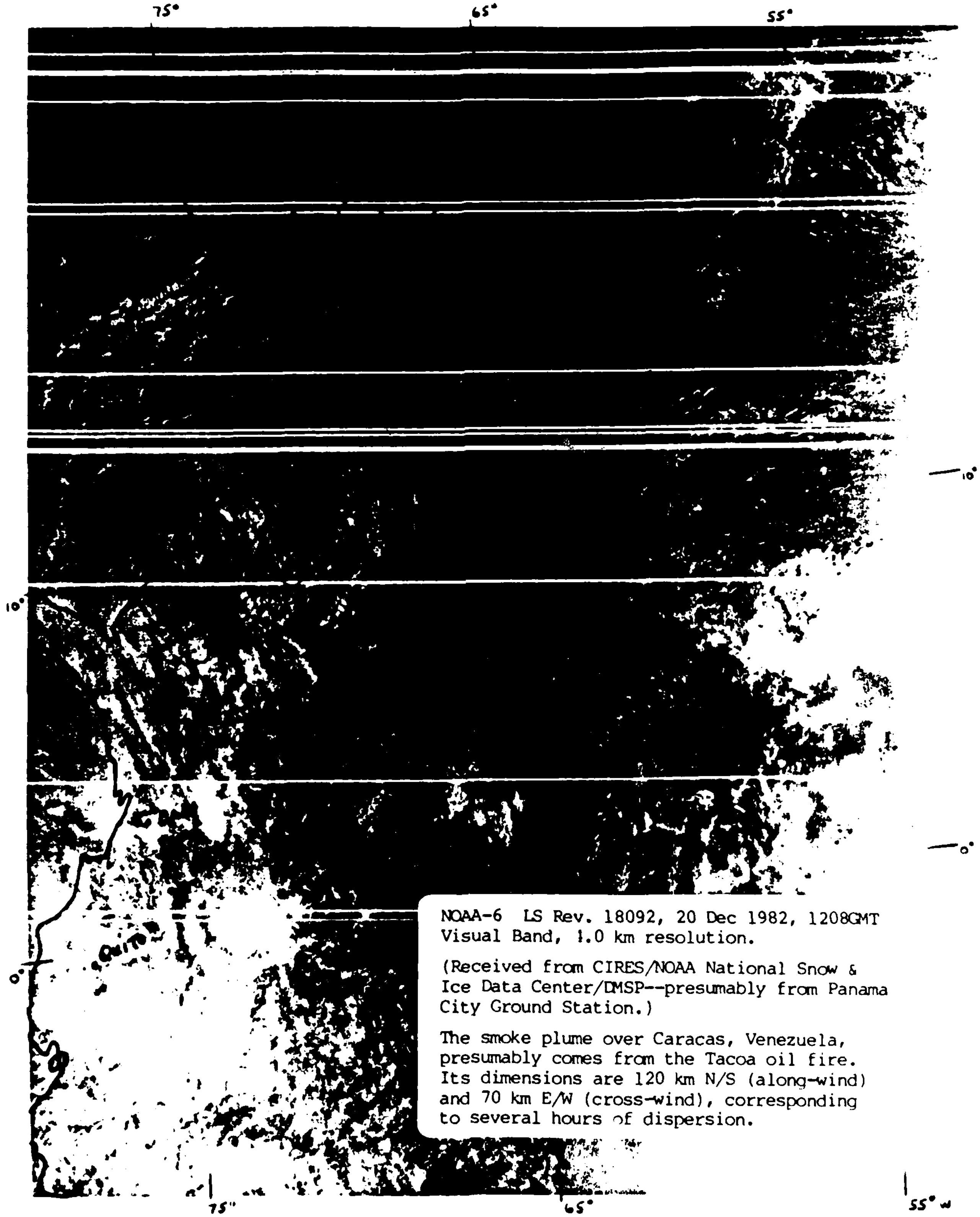

FIGURE B-1. Visible Satellite Imagery from NOAA-6, 7:08 a.m. LT on 20 December 1982 (1 km resolution) showing the smoke plume from the Tacoa, Venezuela oil fire over Caracas.

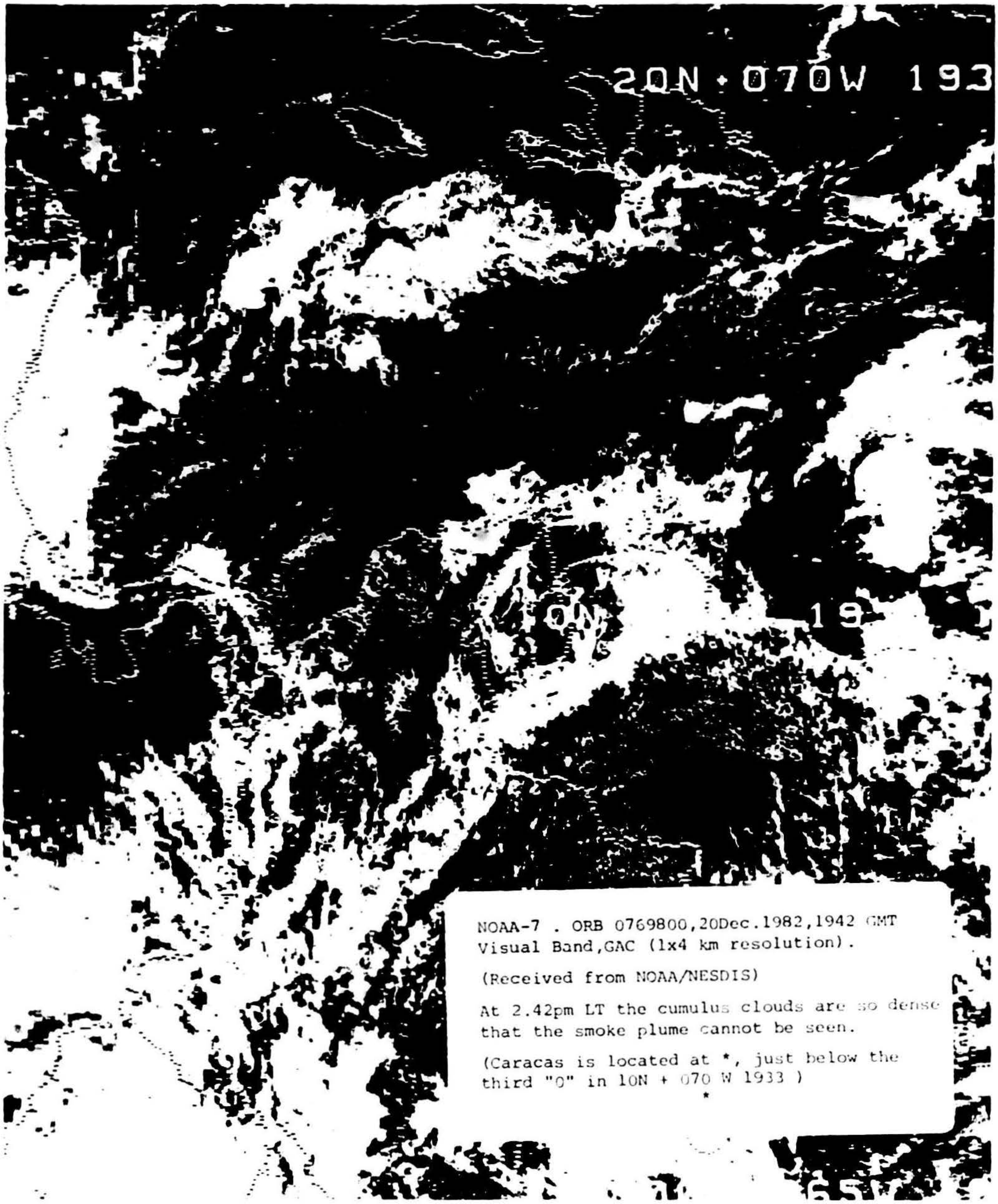

FIGURE B-2. Visible Satellite Imagery from NOAA-7, 2:42 p.m. LT (1 km x 4 km resolution). Note heavy cumulus cloudiness and no sign of the Tacoa smoke plume.

supplemented by the effects of lower resolution and a less favorable sun-cloud-satellite scattering angle.

One may draw the following conclusions from this study:

1. Large forest fires can provide a useful, if partial, simulation of some aspects of Nuclear Winter, in particular: smoke emission, plume spreading, non-uniformity and dispersion/disappearance.
2. Weather satellites provide a useful and inexpensive if incomplete way of studying the time/space development of a series of very large smoke plumes from forest/agricultural or industrial/urban fires.
3. To conduct a useful campaign against such a large fire as an "experiment of opportunity" calls for pre-planning: an appropriate program is outlined in Part I.

One issue which has not been addressed in FY 1985 is the difference in smoke characteristics between forest/agricultural and urban/industrial fires, i.e., between wood and oil or plastics as fuels. While, for example, in the SCOPE briefing at the National Academy of Sciences on 13 September 1985 there is repeated reference to the black, sooty smoke from urban/industrial fires as compared with the white smoke from burning wood (forest fires), above the condensation level in the atmosphere there may be little difference: certainly the oil fire plume of Fig. B-1 does not look much darker than the neighboring water or ice clouds. It may be possible to address late-time soot characteristics, in particular, hygroscopicity and effectiveness as condensation nuclei between wood and oil fires. We know that <u>fresh</u> soot is hygrophobic, and laboratory experiments probably cannot study the properties of <u>aged</u> soot. However, if one can find satellite imagery, in particular multispectral LANDSAT (high-resolution) imagery of oil and forest fires, this may provide quantitative information on the particle growth and change in optical properties over times of hours to days. We hope to begin to address this issue in FY 1986.

APPENDIX C

ATMOSPHERIC MOISTURE AND ITS VARIABILITY

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Figure C-1 shows the atmospheric water vapor mixing ratio as a function of altitude, combining data from the U.S. Standard Atmosphere, 1976 with some "representative" results for Munich in January and July 1985 (kindly provided by Dr. J.K. Angell, NOAA/ARL). Figure C-2 lists the relative humidity as a function of altitude for the U.S. Standard Atmosphere (mid-latitude) and for tropical and subarctic winter models from the IAMAP radiation atmosphere (see McClatchey et al., 1979, essentially an AFGL LOWTRAN model).

At mid-latitudes, the relative humidity in the troposphere is typically 50 percent on the average; in a subarctic winter situation the relative humidity is often higher in the lower troposphere because the air mass has cooled but not lost any moisture by precipitation. In the tropics, the relative humidity is low above the boundary layer (where moisture is picked up from the ocean) except near the (very cold) tropical tropopause which serves as a "cold trap" for limiting the amount of moisture that can enter the (very dry) stratosphere.

Note that the atmospheric "cold trap" works dynamically, not statically. Rising thunder clouds are warmed by condensing excess moisture, which creates buoyancy that enables the cloud to rise higher. The ultimate height limit is set by the very low ambient tropical tropopause temperature and the stability of the lower stratosphere. (For an experimental investigation of the transport of water vapor by tropical thunderclouds see Kley et al. (1982).[1]

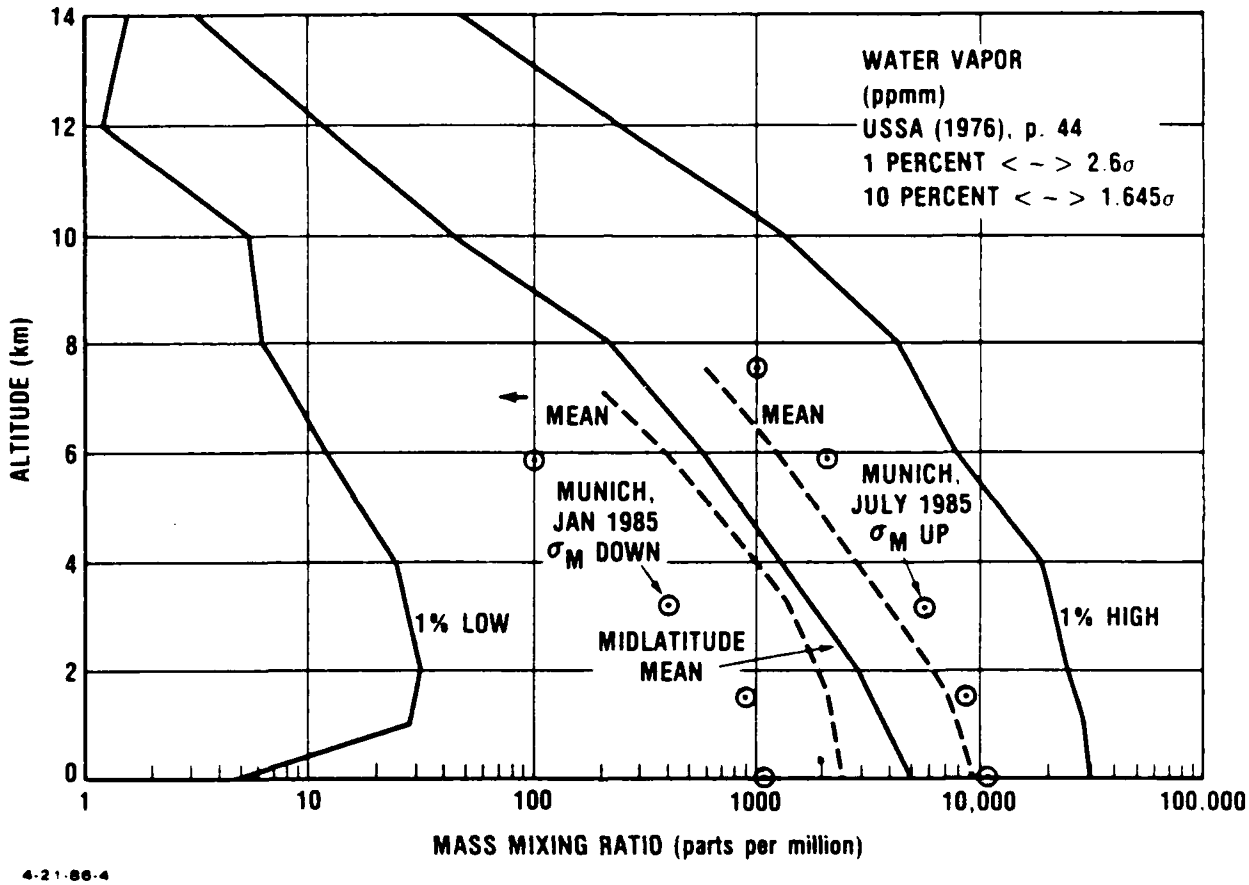

FIGURE C-1. Variability of atmospheric water vapor. (USSA 1976 and Munich January and July 1985)

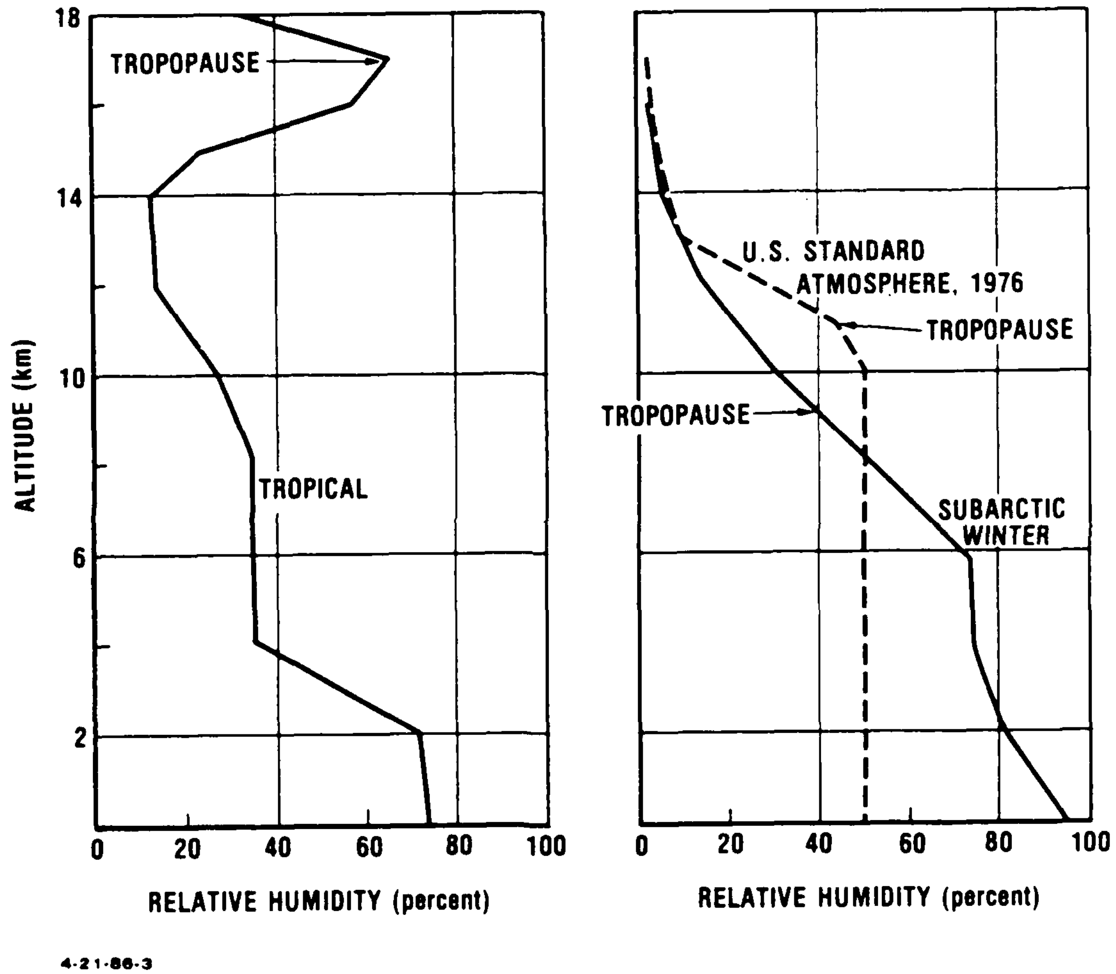

FIGURE C-2. Relative humidity as a function of altitude for IAMAP radiation atmospheres. (McClatchey et al., 1979.)

Table C-1 lists precipitable water integrated from the surface to 500 mb (~ 5.5 km) at selected locations.[2] Note that the total precipitable water varies on the average by a factor of ten between different locations and seasons: at high latitudes in winter (i.e., at very low temperatures) the moisture content is very low ($\lesssim$ 0.5 g/cm^2); at middle latitudes in summer, the moisture is moderately high (~ 2 g/cm^2) while in the humid, maritime tropics the moisture content is very high (~ 4 to 5 g/cm^2).

Smaller scale structure in the water vapor column can be obtained from various satellite sensors:

(a) McMurdie and Katsaros (1985) have analyzed the integrated water vapor column obtained from the scanning multichannel microwave radiometer (SMMR) on SEASAT for a North Pacific cyclone on 10 to 12 September 1978. They find that the water vapor column varies by a factor 10 to 20 as one goes through the surface front of this weather system. Presumably, the same effect is observed on land, but a sea surface provides a particularly benign background for SMMR.

(b) Even smaller scale structure is shown on the "WV" channel (5.7 to 7.1 μm) which is present on the European geostationary meteorological satellite METEOSAT and also on current U.S. GOES geostationary

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[1]At mid-latitudes thunderclouds sometimes rise well into the stratosphere, so that they can serve to transport water vapor to those altitudes. It is not known how effective this mechanism for water vapor transport is, as some of the moisture will go back into the troposphere as the cloud dissipates.

[2]Standard Rawinsonde measurements of dew point (humidity) work for temperatures above -20 to -30 C (~ 400 to 500 mb or 5 to 7 km). At lower pressures (higher altitudes) the air is so dry that reliable measurements of relative humidity cannot be obtained from a Rawinsonde, and in any case the contribution to integrated precipitable water is small. Note, however, that the data base for these high altitudes/low humidities is not good.

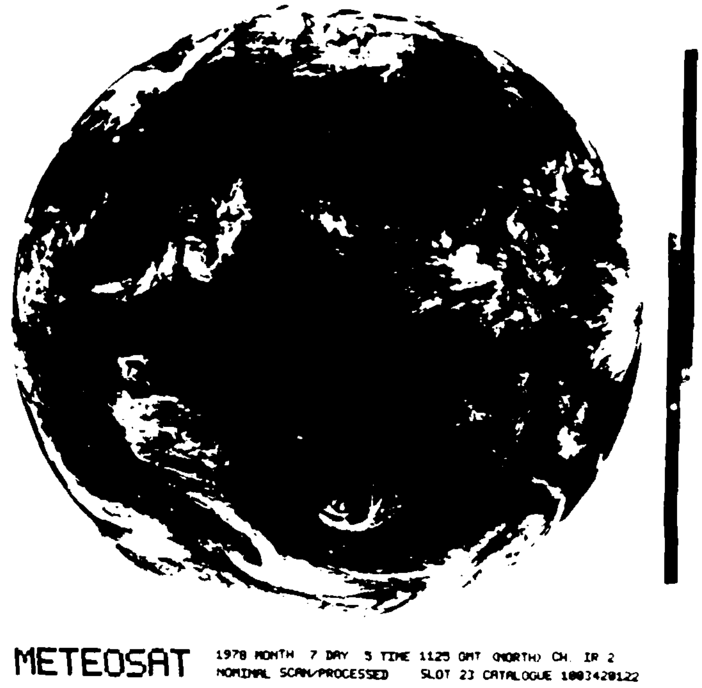
TABLE C-1. PRECIPITABLE WATER (cm, SFC to 500 mb) AT SELECTED LOCATIONS: MONTHLY MEAN AND SOME STANDARD DEVIATIONS

		1984	1985										Standard Deviation	
		D	J	F	M	A	M	J	J	A	S	O	Ja	Jy
Barrow, AK	71°17'N;156°47'W	0.25	0.45	0.33	0.29	0.27	0.73	1.05	1.24	1.26	0.86	0.53		
Brownsville, TX	25°54'N;97°30'W	2.86	2.15	2.44	2.84	2.93	3.65	4.30	4.09	4.21	4.35	3.79	0.25	0.30
Cayenne, S. Amer.	4°56'N;52°20'W	4.68	4.36	4.20	4.48	4.17	4.65	4.88	4.41	4.51	4.25	4.44	0.32	0.22
Kiev, USSR	50°26'N;30°31'E	0.71	0.64	0.46	0.81	1.33	2.00	2.21	2.66	2.56	1.94	1.43	0.11	0.17
Moosonee, Ont.	51°17'N;80°39'W	0.55	0.37	0.47	0.49	0.97	1.16	1.87	2.10	2.24	1.80	1.20	0.06	0.19
Munich, Germany	48°8'N;11°34'E	0.92	0.70	1.76	0.88	1.09	1.79	1.82	2.22	2.23	2.00	1.35	0.13	0.26
San Diego, CA	32°43'N;117°9'W	1.41	1.11	1.06	1.25	1.29	1.48	1.63	2.37	2.07	2.09	1.98	0.13	0.28

Source: J.K. Angell, NOAA/ARL, private communication.

weather satellites. The main contribution to this channel comes from a layer approximately 320 mb thick which lies someplace between the 800 and 250 mb levels (2 to 11 km), depending on temperature and humidity. As an example of this, Fig. C-3 shows roughly comparable IR (10.5 to 12.5 μm) and WV (5.7 to 7.1 μm) views of the earth. The IR channel shows the thermal emission from clouds, while the WV channel also gives a return from water vapor in the atmosphere. Both signals show 64 gray-shades, i.e., the ratio of maximum to minimum intensity that can be obtained from digital imagery can be as much as 64, although the photographic image does not have this wide a dynamic range.

The conclusion is that atmospheric moisture is highly variable, as a function of the "origin" of a particular air mass between the extremes of a cold, dry continental polar (cP) air mass and a warm, wet maritime tropical (mT) air mass. The horizontal scale of a midlatitude air mass is of the order of 1000 km, so that there can be a significant variation in atmospheric moisture at different locations on a particular day, perhaps by an order of magnitude.



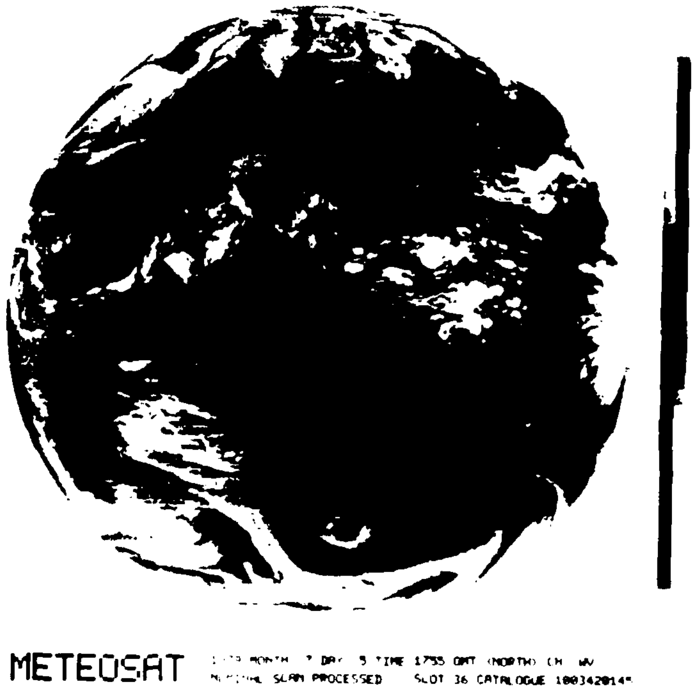


FIGURE C-3. METEOSAT imagery.

Source: Poc et al. (1980)

APPENDIX D

EFFECTS OF CLOUD NONUNIFORMITY

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When a given amount of smoke is injected into the atmosphere, the cloud will hardly ever be distributed uniformly in a horizontal plane (see Fig. 2). The effect of this will be that with a non-uniform distribution (Case 2) more radiation will always be transmitted through the cloud than for a uniform distribution (Case 1), just because of the nature of the (exponential) extinction.

Figure D-1 illustrates this for one example. The total amount of smoke corresponds to an extinction optical thickness X_1 when it is distributed uniformly--in Case 1. In Case 2, the same total amount of smoke is divided between two regions: a region of area A_{thin} in which the optical thickness is smaller by a factor F, i.e., is X_1/F, and another region of area A_{thick} in which the optical thickness has the value F X_1, i.e., is comparably greater. The relative areas A_{thick} and A_{thin} are determined by the condition that the total amount of smoke is the same as in Case 1, i.e.,

$$A_{thick}\ F\ X_1 + A_{thin}\ X_1/F = (A_{thick} + A_{thin})\ X_1 \qquad (D.1)$$

Figure D-1 shows the effective transmittance ratio, T_2/T_1 through the cloud as a function of optical thickness X_1 for representative values of F from 1 to 16, where the ratio A_{thick}/A_{thin} is given by Eq. (D.1). Evidently, for F = 1 there is no non-uniformity so that $T_2/T_1 = 1$, while as both X_1 and F increase, the ratio T_2/T_1 increases. Thus, e.g., for $X_1 = 3$, the ratio $T_2/T_1 = 1.52$ if F = 1.41 or 7.56 if F = 4.

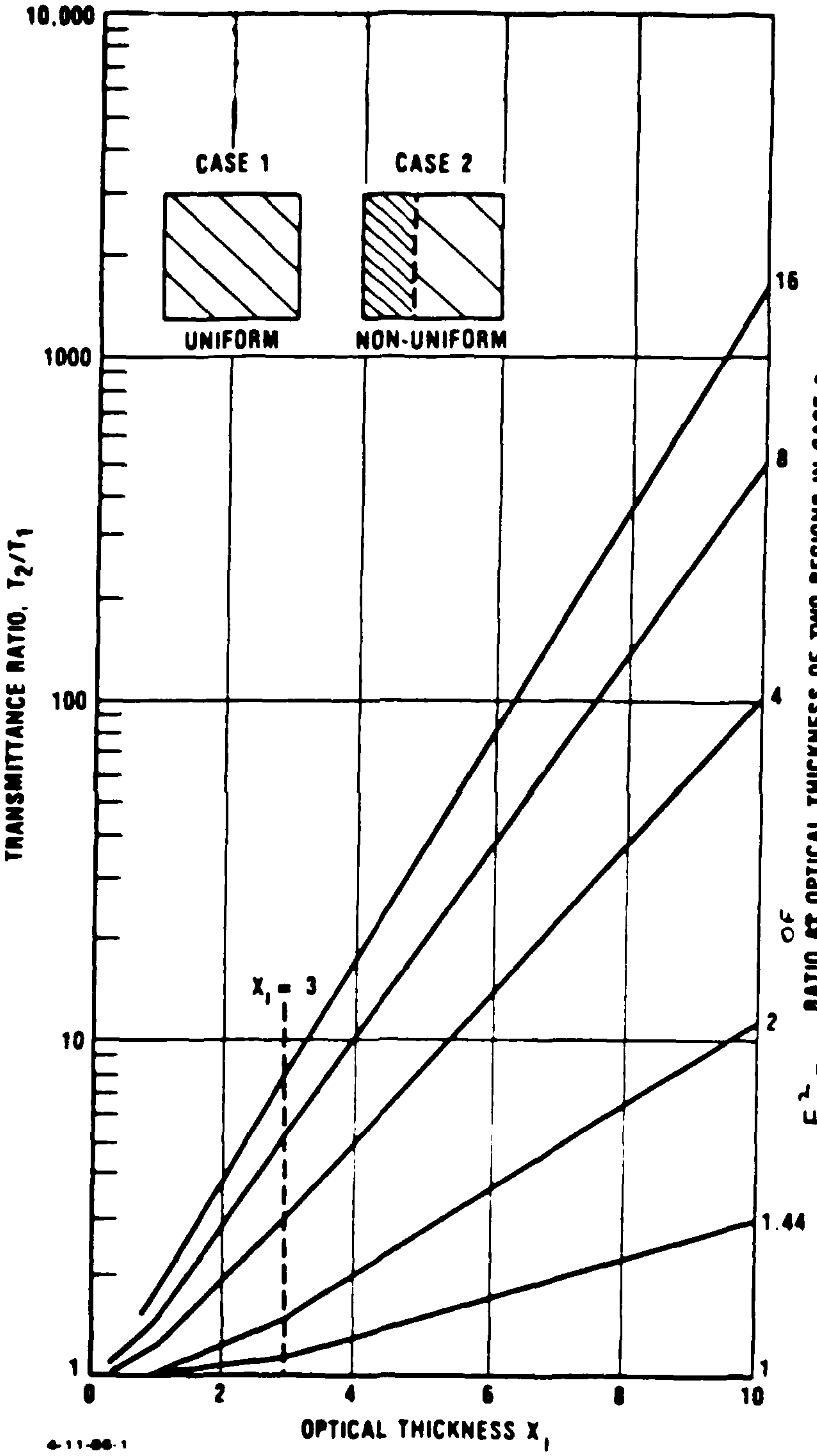

FIGURE D-1. Non-uniform cloud transmits more radiation than a uniform cloud.

It is clearly not possible to make a quantitative estimate of how significant this non-uniformity will be, but a factor of several in the transmission is certainly plausible.